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GENESIS OF THE ORE AT THE FLATHEAD MINE, NORTHWESTERN MONTANA.[1]

PHILIP J. SHENON.

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INTRODUCTION.

THE deposit at the Flathead mine, in Flathead County, northwestern Montana, is reminiscent of the rich bonanza ore bodies of Nevada that have contributed so sensationally to the mining history of the West. Like them, it was formed at shallow depths and during comparatively recent geologic time. Like them also, it contains ore of high tenor enclosed in igneous rocks of late Tertiary age.

The mine is in the SE. quarter, sec. 17, T. 25 N., R. 23 W., about 35 miles by road southwest of Kalispell and 40 miles northwest of Polson. High-grade float was found near the mine in 1913, but no important discovery was made until 1928, when

[1] Published by permission of the Director, U. S. Geological Survey, and the Director, Montana Bureau of Mines and Geology. A paper describing more fully the geology of the Flathead mine and vicinity has been prepared by Philip J. Shenon and A. V. Taylor, Jr., and will be published by the Montana Bureau of Mines and Geology.

leasers found a large and rich body of silver ore. Several hundred tons of ore was shipped before the expiration of the lease, when the Anaconda Copper Mining Company took over the development work. This company continued shipping until October, 1930, when the mine was closed pending an increase in the price of silver. Work was again resumed in January, 1934.

The Flathead mine has produced about 1,500,000 ounces of silver and considerable lead and, without further development work, has assurance of a future tonnage comparable to that already shipped, if not greater. The shipping ore varies in grade, but carload lots average from about 65 to 100 ounces in silver to the ton. Assays indicate a ratio of about 1 per cent. of lead to 8 ounces of silver to the ton.

GEOMORPHOLOGY

The Flathead mine is situated in the Flathead Mountains, one of the mountain units that form the orogenic group west of the Rocky Mountain trench [2] in Montana and east of the Purcell trench in Idaho. The Flathead Mountains are made up principally of a succession of relatively low hills and narrow stream valleys with altitudes ranging from about 4,750 feet on the ridge tops to about 3,000 feet in the vicinity of Niarada. The region is drained by the Little Bitterroot River, a southward-flowing stream, and its principal tributary, Sullivan Creek, but although these streams are perennial, most of the short tributaries that constitute the branching drainage system are dry during the summer and fall.

In addition to normal stream erosion, both diastrophism and glaciation have contributed to the development of the present land forms of the region. The present contour of the Flathead Valley is largely due to block faulting and ice erosion. On the east, the valley is bounded by a great fault, and three successive glacial lobes are believed by Alden [3] to have caused considerable

[2] Daly, R. A.: Geology of the North American Cordillera at the 49th parallel. Canada Dept. Interior, Rept. Chief Astronomer, 1910, vol. 2, p. 117; vol. 3, p. 599, 1913.

[3] Alden, W. C.: Personal communication.

modification as they advanced southward during the Pleistocene epoch. The oldest lobe deposited morainal material as far south as Dixon and Ravalli, whereas the terminal moraine from the youngest has served as a dam for Flathead Lake near the town of Polson. However, the ice sheets apparently did not cover the southern half of the Flathead Mountains, for no evidence of glaciation was observed in the vicinity of the mine.

During the glacial epoch in Montana, ice advanced southward along the Purcell trench in Idaho and temporarily dammed the Clark Fork of the Columbia River, thus forming an inland lake in western Montana, termed by Pardee [4] "glacial Lake Missoula." An arm of this lake extended up the Little Bitterroot Valley and up Big Draw for some distance. The sediments that now occupy the floors of these valleys were laid down in this glacial lake. The short lines are still plainly visible on grassy slopes of many of the hills.

GENERAL GEOLOGY.

Both sedimentary and igneous rocks occur in the vicinity of the mine. The sedimentary rocks are principally argillites of the Belt Series, Pleistocene lake beds, and Recent alluvium along streams. The lake beds occupy the floor of Little Bitterroot Valley several miles south of the mine.

Eleven isolated patches of igneous rocks occur in the vicinity. These rocks represent both intrusive and extrusive types and include latite and trachyte tuffs and agglomerates and porphyritic latites and andesites of both flow and intrusive origin. All the ore thus far produced has come from porphyritic latite that is believed to be intrusive.

THE ORE BODY.

The Flathead ore body is a deposit of irregular outline which trends nearly north and south. The mine openings in October, 1930, were not sufficient to delineate the shape of the ore body completely, but development work up to that time indicated that

[4] Pardee, J. T.: The Glacial Lake Missoula: Jour. Geology, vol. 18, no. 4, pp. 276–286, 1910.

it was roughly elliptical in outline on the upper levels and that cross-sections through it somewhat resembled the cross-sections through a molar tooth with the roots pointing downward (Fig. 1).

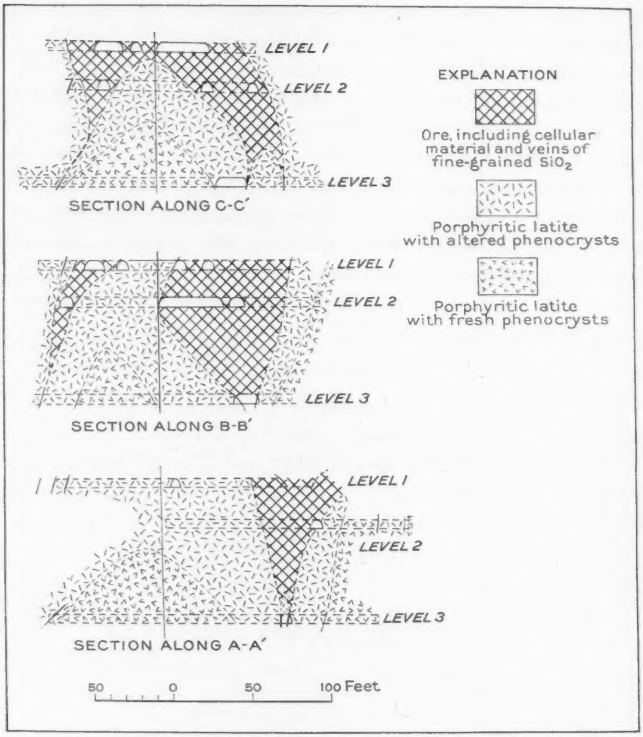


FIG. 1. Geologic cross-sections through the Flathead ore body.

As shown by the development work, the deposit, at its greatest dimension, measures about 150 by 400 feet (Figs. 2 and 3).

The ore occurs in porphyritic latite that is characterized by numerous moderate-sized plagioclase phenocrysts, a lesser number of extremely large sanidine phenocrysts, and some included blocks

of argillite. On the average the phenocrysts make up about 50 per cent. of the rock. The larger phenocrysts are glassy-appearing sanidine; the smaller ones are principally plagioclase with a

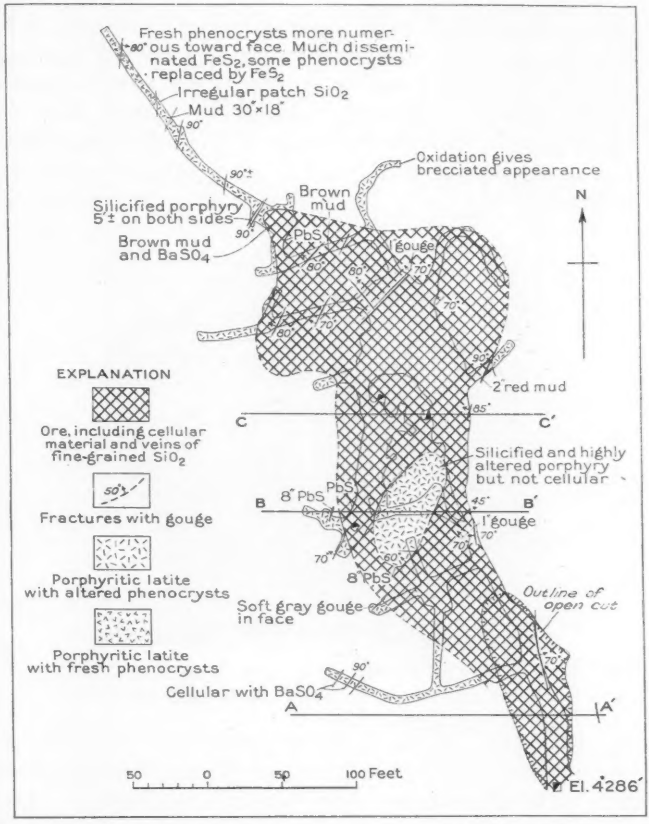


FIG. 2. Geologic map of upper level of the Flathead mine.

composition of about Ab_{70}. Very few phenocrysts of quartz were seen. The groundmass of the porphyritic latite is too fine-grained to distinguish all the minerals even under high magnifica-

tions but it is made up largely of tiny lath-shaped feldspar crystals and some very fine-grained quartz. The sanidine phenocrysts range in length from about 0.5 cm. to over 6 cm., and most of

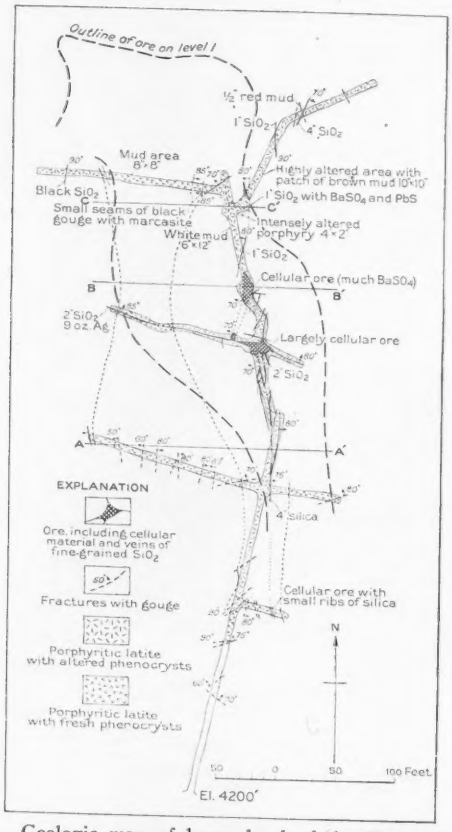

Outline of ore on level I
½ red mud
1' SiO2
4' SiO2
Mud area 8'×8'
Highly altered area with patch of brown mud 10'×10'
Black SiO2
1' SiO2 with BaSO4 and PbS
Small seams of black gouge with marcasite
White mud 16'×12'
Intensely altered porphyry 4'×2'
1' SiO2
Cellular ore (much BaSO4)
2' SiO2 9 oz. Ag
Largely cellular ore
2' SiO2
4' silica
EXPLANATION
Ore, including cellular material and veins of fine-grained SiO2
Fractures with gouge
Porphyritic latite with altered phenocrysts
Porphyritic latite with fresh phenocrysts
Cellular ore with small ribs of silica
N
50 0 50 100 Feet
El. 4200'

FIG. 3. Geologic map of lower level of the Flathead mine.

them show well-developed carlsbad twinning. In general the sanidine crystals have sharp boundaries, and none were observed to be broken. The plagioclase phenocrysts are generally less than

0.5 cm. in length, and most of them show pronounced albite twinning. The outlines of these phenocrysts are generally sharp, but embayments in them are more common than in sanidine crystals.

The porphyritic latite has been altered in different degrees, depending largely upon the distance from the more intensely mineralized areas, but in general sanidine has resisted alteration more than plagioclase. In some places large, fresh crystals of sanidine are associated with entirely altered phenocrysts of plagioclase, and a striking effect is produced where the plagioclase crystals are removed by surface processes (Fig. 4). In some al-

FIG. 4. Fresh sanidine phenocryst in highly altered porphyritic latite, Flathead mine. (Scale in centimeters.)

tered areas the plagioclase phenocrysts and the groundmass are greatly silicified, whereas the sanidine crystals are entirely unaltered. In these places the alteration stops abruptly at the edges of the sanidine crystals. Close to the ore bodies, sanidine and plagioclase are both commonly silicified or altered to clay minerals and alunite. By means of a chemical analysis, Charles Milton, of the U. S. Geological Survey, determined the clay mineral to be largely halloysite. In the ore, many of the phenocrysts of

the prophyritic latite have been partly or wholly removed and are represented by cavities, or casts, some of which are partly filled with barite, fine-grained quartz, and sulphides or their oxidation products. Various stages in the alteration from the fresh porphyritic latite to the cellular stage or the stage where the rock is entirely replaced by barite, quartz, and sulphides may be observed (Fig. 5). For convenience, however, only three stages of

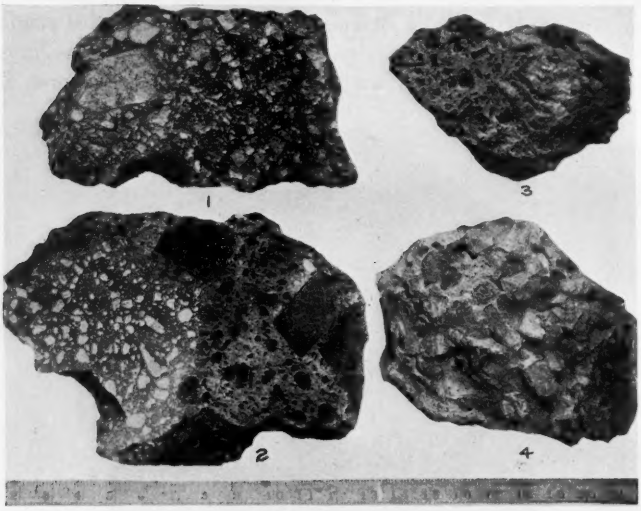


FIG. 5. Series of specimens from Flathead mine, showing gradations from altered porphyritic latite to cellular stage, to stage where cavities are filled or partly filled with barite, quartz, and sulphides, and finally to stage where rock is almost entirely replaced by barite. (Scale in centimeters.)

the alteration are differentiated on the maps: one pattern is used to designate the porphyritic latite with fresh phenocrysts, another pattern designates the highly altered porphyritic latite in which the phenocrysts are changed to clay minerals and fine-grained quartz, and a third pattern is used to designate the cellular ore or veins and irregular patches of quartz.

The silicification varied in intensity; where most intense, it was not confined entirely to fractures, but affected also irregular patches in the cellular ore, generally, however, near fractures. The areas of intense silicification—known locally as " felsite "—are dense, dark gray or black, and commonly include rounded fragments of silicified rock. Some of the fractures containing the dark fine-grained quartz are remarkably continuous, but this is the exception.

In addition to the silicified rock there are throughout the ore body numerous areas of soft, brown, muddy material, composed essentially of iron-rich beidellite with included barite crystals. This material, locally known as " fumarole mud," is found along fractures and as irregular bodies which range from a few inches to over 15 feet in length. The mud is soft and plastic and in the larger areas shows fine laminations which tend to parallel the outline of the material (Fig. 6). Irregular apophyses of the mud

FIG. 6. Banded beidellite mud with some included barite crystals, Flathead mine. (Scale in centimeters.)

extend into the highly altered wall rock, and in one place, in stope 133–R, the mud occupies feldspar casts. Here the mud is in contact with a white chalky-looking rock composed largely of alunite and clay. In cross-cut 108 west, the mud grades rather abruptly into a highly altered alunitic rock stained red by iron oxides but still retaining the texture of the porphyritic latite. This material, in turn, grades into a dense rock composed principally of fine-grained quartz, alunite, and clay. Here and elsewhere, barite crystals are concentrated around the edges of the mud.

Alunitized products formed in the porphyritic latite by alteration processes vary considerably in appearance. In places alunite is associated with white, chalky-looking clayey material which is commonly impregnated with long tabular barite crystals. In another type of altered rock, alunite is associated with fine-grained quartz. This rock is commonly white or light gray and has a good conchoidal fracture. Some of it retains the porphyritic texture of the original rock. Alunite occurs also in tiny hexagonal plates in a highly altered, mottled pink and white porous rock. Jarosite is generally associated with the alunite. No zunyite was recognized.

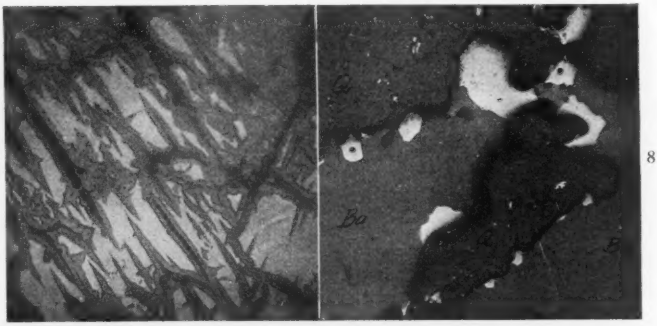
Mineralogy.

The ore minerals at the Flathead mine can be divided into hypogene (primary) and supergene (secondary) sulphides and oxidation products. The hypogene ore minerals include pyrite, galena, antimonial matildite, and small amounts of enargite. Included with the supergene minerals are argentite, small amounts of covellite, and, tentatively, marcasite. W. C. Gallagher has noted the presence of native silver.[5] The matildite ($Ag_2S.Bi_2S_3$) was identified by M. N. Short, who reports good microchemical tests on the mineral for silver, bismuth, and antimony, and negative tests for lead and copper. Because of the presence of antimony, the mineral is better termed "antimonial matildite." Enough of the pure mineral could not be segregated for an

[5] Gallagher, W. C.: personal communication.

analysis, because of its intimate association with galena and supergene argentite (Fig. 7). The matildite is grayish white, somewhat grayer than galena; it is strongly anisotropic and soft; with HNO_3 it slowly stains differentially brown, but when treated with HCl, KCN, $FeCl_3$, KOH, and $HgCl_2$ it gives negative etch reactions.

The gangue minerals associated with the sulphides are principally quartz, barite, clay minerals, and alunite with which some jarosite is generally associated. The more common oxidation



7 8

FIG. 7 (left). Matildite (white) partly replaced by supergene argentite (gray) Flathead mine. Polished section, parallel light. × 290.

FIG. 8 (right). Galena (white) cutting barite (*Ba*) and along contact between barite and quartz (*Q*) with pyrite, Flathead mine. Polished section, parallel light. × 40.

products are anglesite, melanterite, siderotil, some malachite, a yellow amorphous powder containing lead, antimony, and bismuth, and, sparingly, a black manganese oxide. Cerargyrite is probably present near the surface, since exposure of the oxidized ore to sunlight turns some of it to various shades of violet and brown.

Two stages of mineralization are evident. Fine-grained quartz and pyrite were introduced during the first stage. The rock was then fractured and the fractures were healed, largely by fine-grained quartz, barite, and sulphides. Little or no pyrite is associated with the later stage. Barite was not observed cutting the

younger quartz, but because it has a strong tendency to follow the contacts of the older and younger quartz, it is believed to be later than both. Galena is definitely later than the barite. It tends to form at the contacts of barite and quartz and, in some places, follows fractures in the barite (Fig. 8). The matildite is intimately intergrown with the galena. A sparsely distributed mineral gives the etch tests for enargite and could well account for the small amount of arsenic reported in analyses, as well as for the malachite and supergene covellite.

Argentite is by far the most common supergene mineral. In places, particularly on the upper level, it has almost entirely replaced the other sulphides. Covellite occurs only in small amounts and is most commonly found along contacts between anglesite and galena. It occurs less commonly at the centers of residual patches of galena, and in some places as tiny plates stranded in the anglesite. Anderson has pointed out the common occurrence of secondary covellite after galena during the incipient oxidation of galena.[6] Marcasite follows fractures in barite and anglesite and may be supergene, although the evidence is not conclusive.

Enrichment.

Enrichment has been an important process in the formation of the ore, particularly with respect to the silver concentration. The ore minerals were attacked by surface agencies and, because silver in sulphide deposits is soluble as a sulphate in the presence of pyrite,[7] it went into solution and was transported downward to be precipitated as secondary (supergene) argentite. Supergene argentite is abundant on the upper levels, where the sooty-appearing material, known locally as "smoke," is recognized as an indicator of high silver content. The tendency of the supergene argentite to concentrate along fractures is one of the principal reasons for the irregular distribution of silver content in the ore.

[6] Anderson, A. L.: The Incipient Oxidation of Galena. ECON. GEOL., vol. 25, pp. 537–544, 1930.

[7] Emmons, W. H.: The Enrichment of Ore Deposits. U. S. Geol. Survey Bull. 625, p. 253, 1917.

Secondary argentite occurs on the lower level of the mine but in proportionally much smaller amounts than on the upper level.

The more common oxidation products of lead, bismuth, and antimony are relatively insoluble under surface conditions.[8] Since erosion has apparently kept pace fairly well with the oxidation processes, these products have accumulated only in small amounts. Anglesite and a yellow amorphous powder containing lead, antimony, and bismuth, are the most widespread materials developed by weathering.

Genesis of the Deposit.

In considering the genesis of the Flathead ore, attention should be given to the association of alunite with sulphides of lead, silver, and iron; to the nature and occurrence of the irregular patches of beidellite mud; to the age relationships of the ore and gangue minerals; to the depth and temperature under which the deposit was formed; to the origin of the cellular structure; and finally, to the shape of the deposit.

Ore bodies like the Flathead deposit are not common. The meager references in literature to ore deposits associated with alunite is probably due in part to the unusual conditions required for the deposition of ore minerals with alunite and possibly in part to the fact that alunite may be easily overlooked. Ransome[9] has described the occurrence of rare metals in areas of alunitization in the Goldfield district, Nevada, and because of the uncommon association he has designated these deposits the "Goldfield type." The occurrence of base-metal deposits in areas of alunitization may be more common, although a search through the literature has not revealed many records of such occurrences. Alunite is associated with some of the ores in the Bonanza district, Saguache County, Colorado, although the deposits there occur principally as veins.[10] Some of the deposits of the Silver-

[8] Cooke, H. C.: Secondary Enrichment of Silver Ores. Jour. Geol., vol. 21, p. 11, 1931; Emmons, W. H.: *Op. cit.*, pp. 409, 411.

[9] Ransome, F. L.: The Geology and Ore Deposits of Goldfield, Nevada. U. S. Geol. Surv. Prof. Paper 66, p. 199, 1909.

[10] Burbank, W. S.: Geology and Ore Deposits of the Bonanza Mining District, Colorado. U. S. Geol. Surv. Prof. Paper 169, pp. 60, 71, 1932.

ton quadrangle, in southwestern Colorado, as described, appear to resemble the Flathead ore body.[11] They occur in andesite and andesite breccia, which is intensely altered near the ore bodies. The alteration consisted principally of silicification and the development of clay minerals and alunite. Zunyite is associated with the ore at the Zuni mine and in one or two near-by prospects. The ores consisted chiefly of argentiferous galena near the surface but changed at a depth of less than 300 feet to highly argentiferous silver-copper ores, which in turn decreased in value downward with the increase of lower-grade pyritic ores. Bismuth minerals and barite were associated with the ore in many of these mines. In most of them the deposits are described as ellipsoidal masses standing nearly vertical, or as "chimneys."

Alunite has the chemical formula $K_2O.3Al_2O_3.4SO_3.6H_2O$, in which Na may replace K in varying proportions. According to Clarke,[12] it is an abundant and widely distributed mineral associated with altered volcanic rocks, and is commonly derived directly or indirectly from the oxidation of sulphides. It may be formed where ascending solutions containing sulphuric acid attack wall rocks,[13] or where ascending solutions bring in the mineral constituents.[14] Leonard[15] has produced alunite in the laboratory, under varying conditions of temperature and pressure, by treating feldspars with solutions of aluminum sulphate and sulphuric acid, of aluminum sulphate and potassium sulphate, of aluminum sulphate and sodium sulphate, and with a solution of aluminum sulphate alone. More recently J. G. Fairchild, of the U. S. Geological Survey, has prepared several varieties of jarosite, a mineral

[11] Ransome, F. L.: Economic Geology of the Silverton Quadrangle, Colorado. U. S. Geol. Surv., Bull. 182, pp. 214–251, 1901.

[12] Clarke, F. W.: The Data of Geochemistry, 5th ed. U. S. Geol. Surv. Bull. 770, p. 260, 1924.

[13] Clapp, C. H.: Alunite and Prophyllite in Triassic and Jurassic Volcanics at Kynquot Sound, British Columbia. ECON. GEOL., vol. 10, pp. 70–88, 1915.

[14] Butler, B. S., and Gale, H. S.: Alunite, a Newly Discovered Deposit near Marysvale, Utah. U. S. Geol. Surv. Bull. 511, p. 36, 1912.

[15] Leonard, R. J.: The Hydrothermal Alteration of Certain Silicate Minerals. ECON. GEOL., vol. 22, pp. 18–43, 1927.

similar to alunite, by heating certain sulphate solutions at 110° to 200° C. He obtained jarosite only above 110° C.[16]

Butler, Gale, and Loughlin believe that the alunite veins near Marysvale, Utah, were deposited by ascending hydrothermal solutions and that they were formed later and at lower temperature than the valuable metalliferous deposits of the region.[17]

In the Lassen Peak region of California, Day and Allen found that alunite was formed from the alteration of volcanic rocks by the action of hot acid waters.[18] They state:

> The active agents are hydrogen sulphide and especially sulphuric acid. When sulphuric acid decomposes a silicate the final products are free silica and the sulphates of the metals contained in the silicate, and these products are found in all the springs. With them occur two other products of intermediate composition, namely, kaolin and alunite. Kaolin, $Al_2O_3.2SiO_2.2H_2O$, contains silica still unliberated and alumina as yet unchanged to sulphate. Alunite, $K_2O.3Al_2O_3.4SO_3.6H_2O$, contains no silica, but it requires more sulphuric acid to transform its bases into normal sulphates; it is a basic sulphate.

It seems, therefore, that alunite has been formed most abundantly in nature by hot ascending solutions containing free sulphuric acid. Butler states, however, that when sulphur trioxide has developed in a cooling solution to the extent of yielding sulphuric acid, the solution probably ceases to be a carrier of most of the metals.[19] In other words, the conditions favorable for the formation of hypogene (primary) sulphate minerals are not favorable for the introduction of most metals. So far as known, the evidence at the Flathead mine does not conflict with this view, for the barite was clearly introduced after the quartz-pyrite alteration and before the galena and silver minerals. Surface processes have partly obscured the relationships of the alunite, however, so that its history cannot be interpreted with confidence.

[16] Fairchild, J. G.: Amer. Miner., vol. 18, pp. 543–547, 1933.

[17] Butler, B. S., and Gale, H. S.: *Op. cit.*, pp. 21–37; Loughlin, G. F.: Recent Alunite Developments near Marysvale and Beaver, Utah. U. S. Geol. Surv. Bull. 620, pp. 237–270, 1916.

[18] Day, A. L., and Allen, E. T.: The Volcanic Activity and Hot Springs of Lassen Peak. Carnegie Inst., Washington, Pub. 360, pp. 140–141, 1925.

[19] Butler, B. S.: Primary (hypogene) Sulphate Minerals in Ore Deposits. ECON. GEOL., vol. 14, p. 198, 1919.

Some of it may have formed by supergene agencies, but because of its abundance in certain altered areas which contain minerals that are accepted as hypogene in origin, it is likely that most of the alunite is hypogene.

It seems evident that the areas of iron-rich beidellite mud that occur through the ore body, particularly near the edges, have not been derived from the alteration of included rock fragments. There are undoubtedly numerous included fragments in the porphyritic latite, but the mud occupies feldspar casts and follows irregular fractures through the rock, so it is apparent that the material was either formed from the alteration of the porphyritic latite or introduced into it. The presence of barite crystals through the mud, and particularly the marked concentration of barite and alunite around the mud, suggest a genetic relationship, and as the barite is older than the lead and silver minerals it appears likely that the areas of beidellite mud and the altered areas around it are the result of hypogene processes. However, on the basis of present knowledge, it seems likely that the barite was formed under conditions of higher temperature than both alunite and beidellite and that the beidellite, in turn, was formed at a lower temperature than the alunite. Hence, as interpreted, the barite, alunite, and beidellite were formed by solutions of the same genetic source as they passed through the wall rocks but under conditions of decreasing temperature and changing concentrations of sulphuric acid.

The evidence at the Flathead mine indicates that the ore was formed at relatively shallow depths. It is generally agreed that alunite, in the occurrences that have been studied, forms under conditions of shallow depth and moderate heat and pressure.[20] Also, according to Lindgren,[21] barite is most abundant in ore deposits formed at relatively low temperatures (50°–200° C.) and at relatively shallow depths; but, as shown by its occurrence in ore deposits at Ducktown, Tenn., barite is also formed in a high-temperature stage of mineralization.[22] The volcanic rocks in the

[20] Butler, B. S., and Gale, H. S.: *Op. cit.*

[21] Lindgren, Waldemar: Mineral Deposits, 3d ed., pp. 238–519, 1928.

[22] Ross, C. S.: The Copper Deposits of Ducktown Type in the Southern Appalachian Region. U. S. Geol. Surv. Prof. Paper 179, p. 98.

vicinity of the Flathead mine are not found on the highest ridges, and it is probable that the highest ridges were never covered by them. The upper summits are about 4,750 feet above sea level, and the outcrop of the ore body is now at an altitude of about 4,350 feet. Hence, because the ore body is within rocks which apparently did not extend higher than the tops of ridges 400 feet above the mine, it is believed that the deposit was formed at a depth less than 400 feet.

The shape of the deposit is very irregular, but it is fairly well defined by the cellular structure. The cells, which may be empty or partly or almost completely filled with barite and with less amounts of fine-grained quartz, clay, and iron oxides, represent, in part at least, the outlines of formerly existing feldspar phenocrysts. Leaching removed the more soluble minerals, while the less soluble minerals such as barite and quartz were left behind. Barite crystals are suspended in some cavities by a network of tiny quartz ribs in a way that suggests that the rib-like network was developed after the formation of the barite crystals (Fig. 9). If the rib-like network had been formed prior to the deposition of the barite, it would seem reasonable to expect most of the pore spaces between the ribs to be filled or partly filled with barite. Also it would be expected that the barite would have a tendency to grow around the edges of the empty cavities, if the cavities had been formed prior to the barite. Neither condition has been fulfilled. There are many open cavities, but none, so far as known, are lined with barite crystals, and some barite crystals are entirely surrounded by porous networks of quartz ribs that contain no barite. Supergene processes have undoubtedly played a part in the formation of the cellular structure, because sulphides at the surface have been largely oxidized and partly carried away by meteoric solutions, but it cannot be definitely stated that the cellular structure is entirely of supergene origin, as it may possibly have been developed in part by hypogene processes subsequent to the formation of the barite. Nevertheless it seems clear that the cellular structure is largely limited to areas that underwent hypogene mineralization prior to the development of the cellular struc-

ture. Galena and barite are scattered through the cellular ore, whereas little or none of either is known to occur in the porphyritic latite outside the limits of the cellular structure. Hence,

FIG. 9. Cellular ore from Flathead mine, showing empty cavities and cavities partly filled with quartz ribs and barite. (Scale in inches.)

as the cellular structure is limited to the areas in which galena and barite occur, and as galena and barite are considered to be of hypogene origin, it follows that the ore body, as deposited by

hypogene processes, occupied approximately the area now defined by cellular structure.

The shape of the deposit, so far as genesis is concerned, is metasomatically related to two nearly vertical systems of irregular fractures and probably to a set of well-defined flat fractures. One of the vertical systems strikes north and the other slightly south of east. The ore-bearing solutions probably came up along the vertical fractures, particularly along the intersections of strong northerly and easterly fractures, and upon reaching a position where temperature and pressure were favorable, spread out along fractures with flat dips and deposited the ore minerals. The ascending solutions in moving outward from some fractures, particularly some local centers formed by the intersections of strong northerly and easterly fractures, coalesced with solutions moving outward from other fractures and centers, thus giving rise to an ore body somewhat resembling in shape a molar tooth with roots pointed downward.

ACKNOWLEDGMENTS.

The writer wishes to acknowledge the courtesy shown by members of the staff at the Flathead mine, in particular Mr. J. F. Dugan. Discussions with A. V. Taylor, Jr., have been of great benefit, and acknowledgments are due to President Francis A. Thomson and Prof. E. S. Perry, of the Montana School of Mines, for their help and criticisms. Finally, the writer wishes to acknowledge the help and co-operation of his associates of the United States Geological Survey, in particular G. F. Loughlin, R. C. Wells, T. B. Nolan, M. N. Short, W. T. Schaller, Charles Milton, W. C. Alden, and C. S. Ross. Special acknowledgments are due to Mr. Schaller and Mr. Milton for mineral determinations and to Mr. Short for his help during the study of the ore specimens.

U. S. GEOLOGICAL SURVEY,
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THE IDENTIFICATION OF TYPES OF CHALCOCITE BY USE OF THE CARBON ARC.

M. M. STEPHENS.

INTRODUCTION.

THE method, presented in 1931,[1] of identifying minerals by the etching effect of a strong light beam, has proved to be of considerable importance. It has been especially valuable in studies conducted on groups of silver minerals, silver- and gold-bearing tellurides, and copper ores. The ease and accuracy of determining a mineral, and often its geologic history, prompted further research, and for the past two years efforts have been made to increase the usefulness of light and heat etching.

Among the minerals found affected by a strong light or heat beam was chalcocite, and since this mineral is of considerable interest, much of the time available was spent in determining its heat-etch patterns. A great deal can be inferred from the etch pattern that develops during exposure to a heat beam, and by studying this pattern it seems possible to differentiate between hypogene and supergene chalcocite, and also between chalcocite formed from bornite and that formed without relation to any predecessor.

The writer is indebted to Dr. G. M. Schwartz for his continued advice and suggestions throughout the research on this problem. Other members of the Geological Department of the University of Minnesota aided by criticizing the manuscript, and Dr. J. W. Gruner aided in crystallographic studies. Specimens of chalcocite were furnished by Drs. Alan M. Bateman, Donald Davidson, and R. L. Dowdell, who also made several suggestions.

[1] Stephens M. M.: Effect of Light on Polished Surfaces of Silver Minerals. Amer. Min., vol. 16, no. 11, pp. 532–549. Nov., 1931.

SUMMARY OF PREVIOUS WORK.

Little has been published on the subject of light etching since 1931. Schneiderhöhn and Ramdohr's [2] book, in which are described the reactions of stromeyerite to the concentrated rays of an arc light, which are quite like the reactions described in my paper cited above, was published after the paper was in press. Thus, their description was not included in my discussion.

Petrulian [3] produced etch patterns on argentite by use of a six-volt six-ampere lamp, and was able to make an intergrowth visible by etching the argentite.

The writer's previous paper can be summarized as follows:

1. Certain minerals such as argentite, stromeyerite, polybasite, stephanite, pyrargyrite, proustite, pearceite, andorite, petzite, hessite, coloradoite, and others, react in a characteristic manner when exposed to the thermal and actinic rays from a carbon arc concentrated by dry objectives of 8 mm. or 4 mm. focal length or lenses of higher magnification.

2. The speed of reaction varies with the orientation of the mineral and the aperture of the concentrating lens.

3. Andorite, argentite, polybasite, and stephanite yield a sublimate of sulphur which is deposited upon the lens of the microscope.

4. Thermal rays speed up the actinic action, and specimens of petzite, hessite, andorite, stromeyerite and chalcocite react almost entirely to heat.

GENERAL EXPERIMENTAL DATA.

Microscope.—The standard Leitz M. M. micro-metallograph was used for studying the reactions herein described. The unshielded arc-light beam was concentrated by a large condensing lens, and after being reflected by a small movable prism, the rays were concentrated on the polished mineral surface by the objective

[2] Schneiderhöhn, H. and Ramdohr, P.: Lehrbuch der Erzmikroskopie, vol. II, p. 23. Gebrüder Borntraeger, Berlin.

[3] Petrulian, Nikolaus: Über Lichtätzung des Silberglanzes. Schweiz. Min. u Petr. Mitt., Bd. XI, 2, August, 1931.

of the microscope. The polished surface of the mineral to be studied was placed upon the inverted stage. The light was reflected downward into a series of prisms and into the ocular where the reactions could be observed. Most of the reactions could best be observed on the ground-glass plate of the camera attachment. Thus, one was spared the discomfort of the brilliant illumination through the ocular. The normal arrangement of the carbons was found to be most satisfactory.

Adjustments.—It was very necessary to have the light in proper adjustment. The heat rays seemed to travel along the outer boundaries of the bundle of light rays. This possibly is due to chromatic and spherical aberration, since the effect was more noticeable with an achromatic lens than with an apochromatic lens. It was necessary to slide the reflecting prism of the metallograph in its glide in order to reflect the maximum heat on the polished surface.

Heat of the Arc-Light Beam.—In the equipment used, the arc-light crater was 10 cm. from a 5 cm. concentrating lens. This lens converged the light and heat to a small 8 mm. lens located 27 cm. away from the large concentrating lens. At a point immediately in front of the smaller lens, there was enough heat to burn one's fingers. Potentiometer readings with a very small polished thermocouple indicated the following temperatures.

Lens.	Full Light.	Iris Closed to ¼ Inch.
4 mm.	100° C.	68° C.
8 mm.	75° C.	57° C.
14 mm.	70° C.	50° C.

These readings are not accurate because of the great radiation of heat and the difficulty of concentrating a light beam on the couple.

Other methods were tried. Black paper placed at the focal points of the 2 mm. or 4 mm. lens burned almost instantly. A piece of the same paper was placed in an electric furnace which was open to allow free circulation of air, and a thermometer in contact with the paper read 412° C. when the paper flashed. White paper with nearly the same flash point did not burn when

placed at the focal point of the lens. White cardboard with black paper backing burned readily. Water on a polished surface was almost instantly vaporized.

The apparent boiling of sealing wax and the inversion of chalcocite mentioned in a previous paper [4] are indicative of temperatures of at least 100° C. A polished surface of molded sulphur [5] was exposed to the heat concentrated by the 4 mm. lens and the No. 7 Leitz lens without any reaction, but a small fragment was rounded and an odor of sulphur dioxide was given off. A small fragment of the sulphur backed with black paper burned readily. The polished specimen transmitted a considerable quantity of light and heat. Therefore, a specimen transmitting heat will not absorb enough of the arc-light beam to cause a reaction. The writer believes that polymorphous minerals absorbing heat will react to the concentrated heat rays even if the inversion point of the mineral is 250° C. or above.

Laths of covellite apparently dissolved in chalcocite when affected by the strong heat beam. This is in accord with the results of experiments conducted by Bateman and Lasky.[6] They determined the temperature of solution to be as low as 75° C. but stated that more rapid solution occurred at higher temperature. Under the arc-light beam the apparent solution took place if the chalcocite surrounding the covellite was relatively pure and without much dissolved cupric copper.

Short-time experiments using the full heat beam have been conducted over a period of three years, and in spite of the heat developed, no harm has so far been done to the lens system.

REACTIONS OF CHALCOCITE.

General Data.—Chalcocite found in nature occurs in either of two settings, *i.e.* (1) as hypogene material, generally below the

[4] Stephens, M. M.: *Op. cit.*

[5] Sulphur melts at 114.5° C.

[6] Bateman, Alan M.: Some Covellite-Chalcocite Relationships. ECON. GEOL., vol. 24, pp. 421–439, 1929.

Bateman, Alan M., and Lasky, S. G.: Covellite-Chalcocite Solid Solution and Exsolution. ECON. GEOL., vol. 27, pp. 52–86, 1932.

water table, or (2) as supergene material formed usually just below, at, or above the water table. Chalcocite [7] is dimorphous, having an isometric form above 91° C., and on cooling, it inverts to an orthorhombic form. Ford [8] states that artificial crystals of the isometric form show both cube and octohedron with twinning on (111). If 8 per cent. or over of CuS is present in the Cu_2S, it will not invert but will remain isometric.[7]

As is already known, chalcocite may be classified, according to origin, structure, or occurrence, as:

1. Isometric chalcocite. Passing the inversion point without changing structure, thus remaining isometric at ordinary temperature.[9]
2. Coarse-grained orthorhombic chalcocite. Originally above 91° C. but slowly cooled and inverted to orthorhombic form.[9]
3. Chalcocite formed from breakdown or replacement of bornite.[10]
4. Blue chalcocite, three forms of which are recognized—
   a. Generally occurring as isometric chalcocite, the blue color increasing with the amounts of dissolved CuS or covellite present.
   b. Veinlets that cut bornite, chalcopyrite, and pyrite.[11]
   c. Borders around residual masses of bornite, forming an intermediate product between bornite and chalcocite.
5. Chalcocite formed by warm water, but below 91° C.[12]
6. Supergene Chalcocite.

[7] Posnjak, E., Merwin, H. E., and Allen, E. T.: The Sulphides of Copper. ECON. GEOL., vol. 10, p. 513, 1915.

[8] Ford, W. E.: Dana's Textbook of Mineralogy, 4th Ed., p. 419. John Wiley and Sons, 1932.

[9] Bateman, Alan M., and McLaughlin, D. H.: Geology of the Ores of Kennecott, Alaska. ECON. GEOL., vol. 15, pp. 1–31, 1920.

[10] Schwartz, G. M.: Textures Due to Unmixing of Solid Solutions. ECON. GEOL., vol. 26, pp. 739–763, 1931.

Schneiderhöhn and Ramdohr, *op. cit.*, p. 289.

[11] Tolman, C. F., Jr.: Observations on Certain Types of Chalcocite and Their Characteristic Etch Patterns. Trans. A. I. M. E., pp. 402–435, Feb., 1916.

[12] Bateman, Alan M.: *Op. cit.*, ECON. GEOL., vol. 24.

These six forms can be recognized under the microscope by means of etching. Either KCN or HNO_3 will develop etch patterns on the polished surface of chalcocite which indicate, in some cases, whether the material is isometric or orthorhombic. Tolman [11] and Schneiderhöhn and Ramdohr [13] have shown photographically the results of such examination.

The use of the intense beam of the carbon arc described above will also produce a definite pattern on the polished surface of most chalcocite specimens. A classification of the types of patterns produced, based on the study of over 75 specimens from all over the world, is as follows:

(1) Triangular Pattern.
   a. *Butte Type.* Blades of chalcocite oriented triangularly in bornite.
   b. *Kennecott Type.* Isometric chalcocite with a slightly bluish tint.
   c. *Tsumeb Type.* Chalcocite replacing bornite in specific orientations but without blades.

(2) Parallel Pattern.
   a. *Messina Type.* Parallel etch lines, no distortion noted.
   b. *Globe Type.* Distorted etch lines with a general parallelism or granulation.

(3) Blue Etching and Mottled Pattern.
   a. *Impure Chalcocite Transition Type.* Bornite to chalcocite transition.
   b. *Chalcocite Intergrowth Type.* Residual bornite grains intergrown with chalcocite.

(4) Irregular Pattern.

(5) Inactive Specimens. Without pattern.

Triangular Pattern.

Butte Type.—The Butte type (Fig. 1) before etching showed a diamond-shaped or triangular intergrowth between bornite and chalcocite, the latter being in excess. The sharp blades outlining

[13] *Op. cit.*, p. 284, et. seq.

triangular areas are chalcocite and seem to have formed from a breakdown of solid solution of bornite and chalcocite.

When material of this type was subjected to the concentrated thermal rays from a carbon arc light, the bornite areas depressed and the chalcocite areas rose with respect to each other, although this is the reverse of the usual action. Fractures were developed parallel to the chalcocite blades.

Specimens showing a transition of this type into the Kennecott type, *i.e.* with progressively wider chalcocite blades, were not observed, but they may possibly occur. The polished surface may well appear to be pure chalcocite, but if the ore is formed as the Butte type, the triangular pattern will develop on heat etching.

A study was made of a powder residue produced by Forman,[14] who heated copper and sulphur in a graphite crucible for 10 hours at red heat. A briquette was made by compressing this material in a mold at a pressure of 16,000 pounds per square inch, according to the method described by Schwartz.[15] The polished surface of this briquette showed a bladed triangular intergrowth of blue and white chalcocite. Upon etching, this material reacted like the Butte specimen described above, but the blue areas remained unchanged. The blue areas probably were bornite somewhat replaced by chalcocite.

Schwartz developed a pattern resembling the Butte type by heating in a dry sealed tube to 300° C. a specimen from Butte, Montana[16] (65% chalcocite and 35% bornite), forming a solid solution and allowing it to cool slowly. A temperature of 225° C. has been set as the minimum temperature for this reaction. Ray[17] found that a similar structure developed in an aqueous solution at a temperature slightly above 100° C. Experiments made by the writer indicate that this structure does not form artificially

[14] Forman, Fred.: Hydrothermal Experiments on Solubility, Hydrolysis, and Oxidation of Iron and Copper Sulphides. ECON. GEOL., vol. 24, p. 811, 1929.

[15] Schwartz, G. M.: Method of Making Synthetic Minerals for Polished Surface Study. Amer. Min., vol. 17, pp. 478–484, Oct., 1932.

[16] Schwartz, G. M.: Experiments Bearing on Bornite-Chalcocite Intergrowth. ECON. GEOL., vol. 23, pp. 381–397, 1928.

[17] Ray, J. C.: Synthetic Sulphide Replacement of Ore Minerals. ECON. GEOL., vol. 25, pp. 433–451, 1930.

below 100° C. except under high pressure. Specimens were boiled in oxygen-free water for six days without effect. The results of this work will be published later.

Schneiderhöhn [18] believes that such structure is positive proof of hypogene origin for the particular deposit in which it occurs.

Figure 12 shows a triangular replacement pattern that developed when finely crushed Ag_2S and Messina chalcocite were held in a hydraulic press for two days at a pressure of 16,000 pounds per square inch at room temperature. Stromeyerite developed along certain planes which intersected to form triangles. These experiments suggest that triangular replacement may form by pressure, by temperatures above 100° C., or by both.

Thus, if a specimen of apparently pure chalcocite heat-etches in a triangular pattern with intervening blades (*i.e.* Butte Type), keeping in mind the experimental and field relationships, one is justified in believing such a structure was formed at 100° C. or higher, and that the bornite forming the area between the intervening blades was replaced by chalcocite.

Kennecott Type.—The term "Kennecott type" is applied to the typical triangular pattern that develops in isometric chalcocite (Fig. 2). The polished surface shows no residual bornite and has a slightly bluish tinge. Such chalcocite has one of two possible origins; (1) high temperature chalcocite retaining enough covellite in solution to cause the chalcocite to remain in the isometric form on cooling, or (2) a complete chalcocitization of a triangular chalcocite replacement of bornite. Bateman [19] gives the first origin as the most probable, but he also suggests the possibility of the latter in some of the chalcocite of the district, since material of the Tsumeb type also is found at Kennecott.

Tolman [20] believes that all the triangular acid-etch patterns in chalcocite are due to chalcocite replacing bornite along crystallographic planes.

The writer has not made a detailed study of the Kennecott ores because of the lack of a complete suite of specimens. However,

[18] Schneiderhöhn and Ramdohr, *op. cit.*, p. 284.

[19] Bateman, Alan M., and McLaughlin, D. H.: *Op. cit.*

[20] *Op. cit.*, p. 410.

those available clearly showed two types of triangular chalcocite: (1) bluish chalcocite, isotropic under polarized light and containing no residual bornite, and (2) chalcocite similar to the Tsumeb type with chalcocite replacing bornite along crystallographic directions and with residual bluish-pink bornite (Figs. 3, 4). The first type is from ore replacing limestone in such a geologic setting as to strongly suggest hypogene origin.[21] The second type is discussed under the Tsumeb type.

Experiments to be published later by Dr. J. W. Gruner and the writer indicate that blue chalcocite will form at a temperature of 200° C. to 300° C. by the introduction of pyrite into a solution of $CuCl_2$. This chalcocite did not react to the heat rays of the above-mentioned carbon arc. This is no doubt due to dissolved CuS in the chalcocite. After exposure to the heat rays there was no indication of triangular structure, but the material was isotropic under polarized light. The Kennecott type may be formed in such a way as to remain in the isometric form at ordinary temperatures, yet react to the heat rays of the carbon arc, giving the triangular pattern indicated in the photograph. No other chalcocite has been studied in this laboratory that reacted in this manner. All other specimens giving the triangular etch pattern clearly showed early remnants of bornite. As mentioned above, this situation was also found at Kennecott, and Figs. 3 and 4 show such a specimen before and after etching. In the case of the bornite replacement, the heat etching took place rapidly and easily, but the blue Kennecott chalcocite did not react with ease and pro-

FIG. 1. Triangular pattern, Butte type, revealed by heat etching. Note blades of chalcocite that etched out to form the triangular pattern. This structure suggests exsolution and evidence of high temperature. Butte, Montana. × 80.

FIG. 2. Triangular pattern, Kennecott type. Blue, isotropic chalcocite etched by heat. No visible bornite; pattern is weakly developed. Kennecott, Alaska. × 240.

FIG. 3. Chalcocite replacing bornite in triangular replacement. Note sharp contacts, suggesting rapid replacement by solutions under pressure. Kennecott, Alaska. × 104.

[21] Bateman and McLaughlin: *Op. cit.*

FIGS. 1–3. See page 612.

FIG. 4. Triangular pattern, Tsumeb type. Surface shown in Fig. 3, etched by heat. Original bornite areas turn blue and fade into chalcocite. Kennecott, Alaska. × 104.

FIG. 5. Triangular pattern, Tsumeb type, showing second generation of chalcocite cutting the triangular pattern. The veinlet gives an acid reaction typical of orthorhombic chalcocite but is devoid of supergene characteristics. (See Fig. 7.) × 104.

FIG. 6. Bornite grain replaced by chalcocite. The two reaction rims are shown,—(1) a triangular intergrowth, and (2) a blue tarnished area. Neither was visible before etching. Messina, So. Africa. × 120.

duced only a faint etch pattern. Thus, keeping the above facts in mind, bluish chalcocite that etches with difficulty and produces a faint triangular pattern (as shown in Fig. 2) is undoubtedly hypogene chalcocite formed above 90° C.

Tsumeb Type.—The Tsumeb type is a triangular etch pattern formed in chalcocite that has replaced bornite along triangular or crystallographic planes. The term simply applies to one type of pattern developed diagrammatically in the ores of Tsumeb, as shown by Schneiderhöhn.[22] This type differs from the Butte type in that the chalcocite did not etch out as blades, but there may be a possible relationship.

Figure 3 shows the original bornite-chalcocite relationship before being subjected to the heat of the carbon arc. The chalcocite cuts the bornite along certain oriented lines. The contacts are mostly parallel, suggesting that the replacement took place under pressure or rapidly while both bornite and chalcocite were isometric, thus at a temperature above 91° C. The replacement pattern certainly was governed by the structure of the replaced bornite. As discussed later, secondary replacement generally does not show such sharp contacts and such regularity in the patterns.

After exposure to heat, the pattern developed was diagrammatically triangular and isometric. Bornite areas did not react to the heat beam except to tarnish blue, but the contact of this material with chalcocite was accentuated by a crack, fracture, or *etch line*. It is the joining up of these etch lines that gave the typical triangular pattern illustrated in Figs. 4 and 5.

Areas in chalcocite not showing remnants of bornite etched in a parallel pattern described later as the Messina type. Fig. 5 shows chalcocite of two generations and types. The first generation replaced bornite, whereas the later generation cut the triangular areas as veinlets. HNO_3 or KCN, when placed on a freshly polished surface of the bornite intergrowth, developed a triangular pattern, as in the photographs, but when the veinlets of chalcocite that cut the intergrowth were etched by the reagents, an irregular granular pattern developed. This latter reaction, according to

[22] Schneiderhöhn, Hans, and Ramdohr, Paul: *Op. cit.*, p. 284.

Tolman,[23] is typical of orthorhombic chalcocite that was formed below 91° C. without relationship to bornite.

The development of the triangular pattern from bornite is illustrated in Fig. 6. This material from Messina, So. Africa, shows that the original bornite grain extended beyond its present outline to the edge of the irregularly etched areas. Enlargement of the bornite boundary outlined in ink shows that this area is of the typical triangular type, although not as regular as Figs. 4 and 5.

Material from Mufulira Mine, Africa, also shows a triangular intergrowth between bornite and chalcocite along veinlets that cut the bornite. The chalcocite here clearly replaced bornite and also replaced chalcopyrite to a lesser degree. The centers of the veinlets were free of bornite but chalcocite commonly graded inward into pure bornite by passing through the following stages: blue chalcocite triangularly intergrown with white chalcocite; massive blue chalcocite; blue chalcocite triangularly intergrown with bornite; finally, in many cases, pure bornite. These stages do not always exist, and commonly only bornite was found intergrown with chalcocite. Either type of intergrowth shows sharp boundaries between the two minerals. Possibly if the replacement temperature was below 91° C. the contacts would be more irregular and would not develop the triangular patterns unless replacement took place under considerable pressure. Experiments carried on jointly with Dr. Gruner indicated that considerable replacement of bornite by chalcocite occurred at temperatures slightly less than 100° C., if slight amounts of $CuCl_2$ were present in water. The replacement at this temperature was always irregular and devoid of diagrammatic patterns. If higher temperature was used, *i.e.* above 150° C., the replacement tended to take place along certain crystallographic planes. Both bornite and chalcocite were isometric at these temperatures; thus isometric replacement patterns were developed. Gruner[24] pointed out that replacement of bornite by isometric chalcocite was along (111)

[23] *Op. cit.*, p. 406.

[24] Gruner, J. W.: Structural Reasons for Oriented Intergrowths in Some Minerals. Amer. Min., vol. 19, pp. 227–237, 1929.

planes and that there was a structural reason for such a replacement.

Tolman [25] states, " No isometric etch figures have been found in natural chalcocite that are not inherited after some antecedent mineral, generally bornite."

Tolman [26] also says,

> My studies indicate that the pseudomorphic etch pattern may develop great regularity (Fig. 27) and that a triangular or rectangular pattern in natural chalcocite in which all three directions of cleavage are equally regular proves it to be a replacement of an earlier mineral, generally of bornite.
>
> I have found two types of etching in a single grain of chalcocite (Fig. 28), a beautiful isometric etch figure in the center where the original bornite structure controls, and a fine mosaic of striated orthorhombic crystals on the outside, where the replacement destroys instead of preserves the original bornite structure.

The writer believes that the sharp triangular replacement is indicative of replacement of bornite by chalcocite above 100° C., but that triangular patterns may exist in chalcocite if formed as mentioned under the Kennecott type. The sharp triangular replacement should be distinguished from the roughly triangular and irregular replacement of supergene action.

In general, the Tsumeb type is recognized primarily by the presence of remnants of partially oriented bornite (in the unetched specimen) and the development of the diagrammatic triangular pattern when exposed to heat. This type, however, did not show any blading like that discussed under the Butte type.

Parallel Pattern.

Messina Type.—This type of heat etching developed to its greatest extent in the specimens from Messina, Transvaal, Africa. The specimens studied were unusually pure white chalcocite and contained only a few small grains of bornite.[27] This material was

[25] *Op. cit.*, p. 412.

[26] *Op. cit.*, p. 400.

[27] Analysis by Dr. R. Ellestad: Cu, 79.24%, S, 20.20%, Fe, 0.20% = Total, 99.64%.

very massive, and some broken edges showed parting. Reactions with HNO_3 indicated a directional blading; a few small areas gave the typical granular orthorhombic pattern.

When the polished surface was exposed to the concentrated heat rays of the carbon arc, a parallel blading appeared (Fig. 7). The etch lines literally flashed into view, progressing away from the area of maximum heat concentration. The lines seemed to be oriented in certain crystallographic directions, and different positions of the grains were indicated by a change in direction of the etch lines. The lines in the coarse-grained material predominated in one direction, with the lines of other grains appearing at every possible orientation. Right angles were common, but acute and equilateral triangles were formed to a lesser degree.

If exposure was made after the etching had taken place, the surface of the mineral would tarnish iridescent, and where the heat was great enough small triangles formed. Pits have been burned into many specimens because of over exposure. This indicated that the temperature of the arc-light beam was high above the inversion point of chalcocite, and possibly chalcocite absorbs enough heat to reach the disassociation temperature.

There was a volume change indicated by an enlarging of fractures along the etch direction. This change varied somewhat but was estimated at 2 per cent. or more of the visible field. The inversion of chalcocite from the orthorhombic to the isometric system is accompanied by a decrease in volume of about 2.6 per cent. and by the development of polysynthetic twinning lamellae.[28] There is little doubt that the same change took place in view under the microscope when the specimen was subjected to the treatment described above. Therefore, the described etch lines in this case were caused by the development of polysynthetic twinning lamellae. This reaction affected a thin surface layer and remained after the heat beam had been removed. Specimens left for longer

[28] Posnjak, Merwin, and Allen, in *op. cit.*, give the specific gravity of orthorhombic chalcocite as 5.802.

Barth, T. (Die Reguläre Kristallant von Kupferglanz; Centr. f. Min. 1926–A, p. 284) gave isometric chalcocite the specific gravity of 5.97. Thus a change of about 2.6% in volume occurs in the change from orthorhombic to isometric.

than six months still showed etch lines apparently as prominent as at the time of formation. It is probable that the sudden removal of intense heat from the visible field acted the same as quenching.

This reaction was also found in the ores of Butte, Montana; Bisbee, Globe, and Ajo, Arizona; Tsumeb, Mufulira, and Roan Antelope, Africa; Zinnwald, Saxony; Langban, Sweden; Bristol, Connecticut; Cornwall, England; and many other places.

Specimens from Cornwall, England, and Bristol, Connecticut, showing well developed orthorhombic crystals, were found to etch in the same manner described above but with the etch lines more closely spaced. No bornite is seen in these crystals.

Bateman [29] points out that the crystals examined from Bristol must have been formed below 91° C. because their outer form was orthorhombic and showed no signs of having been isometric. Using the alteration of the wall rock as a guide, he says: [30]

> The most outstanding inference is that the solutions which brought the copper were not highly heated, otherwise more intense wall-rock alteration would be expected. . . . The Bristol chalcocite is shown to have no dissolved covellite, so that inversion to the orthorhombic form would be expected had it originally been above 91° C. However, the Bristol crystals show no indication of ever having had an isometric form or structure. On the contrary, all the crystals have clearly defined external orthorhombic form. If the findings of the Geophysical Laboratory investigations be accepted as applying to nature, it would follow that the orthorhombic crystals of Bristol were formed at a temperature below 91° C.

Two acid-etch patterns were seen in orthorhombic hypogene chalcocite of the Messina type, *i.e.* a parallel type and a granular type. Supergene chalcocite also gave a granular etching. It is, therefore, impossible positively to distinguish low-temperature hypogene chalcocite from supergene chalcocite by means of reagents. In the specimen shown in Fig. 5, chalcocite has replaced bornite, forming a triangular heat-etch pattern, the latter

[29] Bateman, Alan M.: Personal communication.

[30] Bateman, Alan M.: Primary Chalcocite, Bristol Copper Mine, Conn. Econ. Geol., vol. 18, pp. 160–161, 1923.

being cut by veinlets of chalcocite, which gave a fine-grained acid etching; but when exposed to heat, it gave a parallel etch pattern quite like that of Bristol, Connecticut, and Cornwall, England. The veinlets were probably formed by warm solutions. Thus, if a specimen of chalcocite acid etches in a granular pattern but gives a parallel heat-etch pattern, it was probably formed below 91° C. by hypogene solutions. In this case it is possible to differentiate between chalcocite formed above and below 91° C. by using both heat and acid methods of study. Some apparently orthorhombic chalcocite from St. Ives, Consols, Cornwall, England, gave a parallel etch pattern, with both heat and acid. This is the only example of chalcocite formed below 91° C. that gave a parallel pattern for both acid and heat. The outward crystal form was orthorhombic; thus the formation must have been below 91° C., and the parallel pattern suggests hypogene origin.

Globe Type.—The heat-etch pattern of Fig. 8, taken from Globe, Arizona, seemed to be of the parallel type with some distortion. This same pattern was developed artificially by mounting a piece of Messina chalcocite in Woods metal (melting point 71° C.) and subjecting it with a slight rotational stress to 16,000 pounds pressure per square inch for two days. The etch lines could be bent by applying lower pressures, or could be crushed by rotational stress (Fig. 7), thus resembling steely chalcocite from Butte, Montana. If subjected to greater pressure than 16,000 pounds, and for a longer period than two days, other patterns developed, some of which were triangular.

Material showing a granular pattern has at least three possible origins: (1) from rapidly cooled, low-temperature, hypogene solutions, (2) from the crushing of chalcocite formed at temperatures above or below 91° C., or (3) from supergene solutions. Chalcocite formed by conditions 1 or 2 shows polysynthetic twinning lamellæ but with no general orientation. Specimens studied known to be supergene did not give a granular pattern with twinning, but gave instead an irregular etching, as described later. As far as the patterns formed by the crushing of the ore are concerned, more work must be done along these lines before a definite conclusion can be drawn.

In material that shows a parallel pattern in heat etching, high-temperature hypogene chalcocite can generally be distinguished from low-temperature hypogene chalcocite by comparing the acid-etch patterns with the heat-etch patterns. Orthorhombic chalcocite formed above 91° C. is generally coarse-grained, with evident twinning when etched with acid; whereas that below 91° C. is generally more granular and with subordinate twinning on the grains. Chalcocite formed by hot or warm solutions and without relation to bornite, developed grains with a heat-etch pattern that predominated in one direction and was due to the development of polysynthetic twinning lamellæ. Distortion of the mineral is evident if the twinning lines are bent or strained.

Mottled and Blue Etch Pattern.

Impure Chalcocite Transition Type.—Some specimens developed blue areas over the surface when exposed to the heat beam. Generally these blue areas were granular or spotted and seemed to have a shape governed by some mineral predecessor. Often small remnants of pink bornite were found outlining or joining the blue etched areas. Fig. 9 shows a shard invisible in the original section but blue after etching. This connects with a small fragment of bornite at the upper edge of the photograph. No doubt this entire area was at one time a piece of bornite and now it is almost completely replaced by chalcocite. Why the replacement did not take place along certain lines or directions is not known, but possibly, as discussed above, the temperature and pressure at which the replacement occurred influenced crystallization. Transition zones were sometimes noted on such grains as shown in Fig. 6, but here it passed into a triangular replacement

FIG. 7. Parallel pattern, Messina type. Pure coarse-grained chalcocite heat-etched with 4 mm. lens. Etch lines are caused by development of polysynthetic twinning lamellæ. Pietersburg, So. Africa. × 220.

FIG. 8. A variation of the parallel etch pattern, possibly caused by pressure on the ore. Chalcocite is mottled blue and white; blue changes in relief but does not form twinning lamellæ. Note blue area—impure chalcocite formed from bornite—in upper right corner. Globe, Arizona. × 80.

FIGS. 7–8. See page 620.

FIG. 9. Etched surface of chalcocite which has replaced bornite. No bornite fragments remain in this replacement by chalcocite. Butte, Montana. × 220.

FIG. 10. Intermediate stage in development of mottled etch pattern. Bornite grains with blue impure chalcocite borders. Less intense heat etching produces further development of the mottling. × 112.

FIG. 11. Chalcocite, apparently supergene, heat-etched to bring out structure. Inspiration, Ariz. × 124.

FIG. 12. Stromeyerite formed along pyramidal (or octohedral, if isometric) planes. Powdered Ag_2S and finely crushed Messina chalcocite were held at 16,000 pounds pressure per square inch for two days. Note triangular replacement quite like the Butte type. × 128.

frequently observed. These two types of blue etching were not entirely comparable, since the case first cited seems to be nearer the end of the change from bornite to chalcocite. However, generally speaking, most areas that etched blue indicated the original presence of bornite that had been enriched in copper but possibly was not entirely free of either iron or cupric copper.

Chalcocite Intergrowth Type.—Many specimens developed a mottled appearance when starting to react to heat. Small peg-shaped or irregularly shaped grains were scattered throughout a groundmass generally lighter in color. The grains commonly occurred in specimens showing the blue etched areas described above. The relationship of the peg-shaped grains and the general groundmass suggested the bornite chalcocite structures in the experiments described by Schwartz.[31] The mottled surfaces were generally masked by the development of etching of the parallel type upon longer exposure to heat.

A specimen from Butte (about 65% chalcocite and 35% bornite) artificially heated to 300° C. was quenched, thus retaining a solid solution.[32] This material gave a mottled appearance when heat-etched.

Bateman and Lasky [33] suggested that mottled chalcocite was due to covellite unequally dissolved in the chalcocite. Two origins of the mottling, therefore, have been suggested,—the one from bornite, the other from covellite. If the mottling is from bornite, then it is due to unreplaced iron, unless bornite contains cupric copper which remains instead of iron when the bornite is partially replaced by chalcocite. If the latter is the case, the accepted formula for bornite ($5Cu_2S \cdot Fe_2S_3$) should include the cupric copper. It is also possible that the partially replaced bornite contains excess sulphur left by the removal of iron, and the cuprous copper oxidizes when exposed to the intense heat beam. If the mottling is due to cupric copper, then all mottling in chalcocite can be referred to the unequal distribution of CuS in solid solution with chalcocite. Fig. 10 shows bornite changing to

[31] Schwartz, G. M.: *Op. cit.*, ECON. GEOL., vol. 23.
[32] *Idem.*
[33] *Op. cit.*

chalcocite, with a blue transition zone around each grain. It also shows how the parallel etching tends to obliterate the mottling. Pseudo-eutectic [34] relationship between bornite and chalcocite will form mottling if further chalcocitization replaces or partly replaces the bornite.

Specimens from Butte, Montana; Globe, Bisbee, and Ajo, Arizona; Messina, Roan Antelope, Africa; Seigren, Westphalia; and Engles, California, show this type of etching.

Considering the similarity and relationship of the mottling to bornite structures found in chalcocite when heat-etched, one is justified in suggesting that the mottled surface is generally due to impure remnants of nearly completely replaced bornite.

Irregular Patterns.

Certain specimens subjected to heat rays gave etch patterns unlike any of those described above. The surfaces of this group etched in an irregular fine-granular pattern (Fig. 11). Generally speaking, the sections contained covellite, calcite veinlets, and irregular replacement along veinlets, and were found near the surface of the vein from which they came. These specimens seemed to be supergene.[35]

The explanation of the fine irregular pattern possibly can be found in a discussion of acid-etch cleavage. According to Graton and Murdock,[36] it is suggested that chalcocite deposited by ascending solutions possesses good etch cleavage, while supergene chalcocite shows countless irregular cracks. Tolman says:[37]

> According to my observations, the etching of that variety of orthorhombic chalcocite which is an aggregate of minute crystals develops the outlines of the irregular but roughly equi-dimensional crystals, each crystal having a fine lining or striation in one direction. Coarsely

[34] Shown photographically by Bateman. Ores of Northern Rhodesia Copper Belt. Econ. Geol., vol. 25, Fig. 10, p. 395, 1930.

[35] Schwartz, G. M.: Microscopic Criteria of Hypogene and Supergene Origin of Ore Minerals. Econ. Geol., vol. 27, pp. 533–553, 1932.

[36] Graton, L. C., and Murdock, J.: The Sulphide Ores of Copper. Trans. A. I. M. E., vol. 45, pp. 26–81, 1913.

[37] *Op. cit.*, p. 403.

crystalline orthorhombic chalcocite, however, is characterized by an etch pattern which is stronger and more regular in one direction than in the other direction. (Illustrations 38, 39, 40).

This same feature is true in heat etching, *i.e.* coarsely crystalline chalcocite develops polysynthetic twinning or isometric figures, but finely crystalline chalcocite develops the fine irregular etch pattern shown in the photographs.

Criteria, therefore, for distinguishing hypogene from supergene chalcocite are that hypogene chalcocite is coarse-grained and etches in either the triangular or parallel types, whereas supergene chalcocite is fine-grained and etches in the irregular type.

Inactive Specimens.

This term applies to chalcocite that does not yield an etch pattern.

Only two main types of chalcocite were negative to the heat action—(1) some secondary material, and (2) blue chalcocite.

The chalcocite of supergene origin generally occurs (1) replacing wood, (2) as concentric or colloform structure, (3) as sooty chalcocite, or (4) as blue chalcocite. In the case of white supergene chalcocite a reaction may have occurred, but the fineness of grain is such as to make any change invisible at high magnification. On the other hand, the material may have been so impure that no change took place.

Blue chalcocite seems to be of three general types—(1) formed from bornite or other iron-bearing copper minerals by the action of warm solutions; (2) formed from hypogene solutions high in cupric copper, thus precipitating a high cupric copper chalcocite; or (3) formed by an extremely fine intergrowth of covellite and chalcocite. The latter is generally supergene or very low-temperature hypogene. As mentioned above, the heat etching is possibly due to inversion of chalcocite from orthorhombic to isometric form, or at least from one space lattice to another. It has been mentioned above that over 8 per cent. cupric sulphide inhibits the inversion of chalcocite. This inhibition may also be caused by iron or a combination of iron and cupric sulphide.

Material from Butte, Montana,[38] heated to 300° C. to form a solid solution and held in that form by quenching, would not react to the heat beam. Varying proportions of silver were added to pure chalcocite used in experiments for Schwartz,[39] and the same examined for heat-etch reactions. These experiments indicate that 10 per cent. silver sulphide will prevent such a change. The writer believes that many elements can be found which will prevent an inversion or change in chalcocite if they occur in excess. Possibly the explanation of the inactivity of the above-mentioned secondary material lies in the same category.

Only a small percentage of the many specimens studied were inactive, and those mentioned were all of a very special type seldom found in the average deposit. These types can usually be identified readily by other tests and therefore cause no particular difficulty in the application of heat etching in determining the type of chalcocite.

APPLICATION OF HEAT ETCHING.

The following report covers a specimen of copper ore from Butte, Montana, and is given here to show how microscopic heat etching and acid etching can be used to interpret micro-relationships.

Specimen—Univ. of Minn. No. B-1690. Butte, Montana. Mine unknown.

Minerals—Covellite, chalcopyrite, bornite, blue and white chalcocite.

Polished Surface Relationships.

Covellite.—Several large blades of covellite are abundant throughout the entire surface of the specimen except for breaks caused by veinlets of bornite and chalcocite. The contact between the veinlets and the covellite is irregular and the covellite appears corroded, suggesting that the latter mineral is replaced by bornite and chalcocite.

[38] Schwartz, G. M.: *Op. cit.*, ECON. GEOL., vol. 23.

[39] Schwartz, G. M.: Relations of Chalcocite-Stromeyerite-Argentite. ECON. GEOL., vol. 30, pp. 128–146, 1935.

Chalcopyrite-Bornite-Chalcocite.—Small blades of chalcopyrite are found in the bornite, which cuts the latter mineral leaving a very smooth contact, suggesting that there has been very little or no replacement, but that the two minerals in this case are contemporaneous. Chalcocite cuts and corrodes bornite, leaving irregular grains of the bornite scattered throughout the chalcocite.

Blue and White Chalcocite.—The chalcocite occurs in two colors, *i.e.* white and blue. The blue areas are only slightly so, and would not be noticed except for the presence of white chalcocite which surrounds, cuts, corrodes and replaces the bluish areas.

Acid Etching.—HNO_3 brings out three patterns—(1) a parallel type, typical of coarse-grained orthorhombic chalcocite, (2) a granular type, typical of low-temperature chalcocite, and (3) a triangular type, typical of high-temperature chalcocite.

Heat Etching.—The chalcocite around the covellite does not etch with ease, and when it does etch, the pattern is coarsely triangular, suggesting that the material replaced covellite at a temperature above 91° C. and dissolved enough covellite to keep the chalcocite in the isometric state at room temperature.

The other blue chalcocite turns a darker blue than before, and its areas can easily be traced to residual grains of bornite. The area as a whole clearly suggests the replacement of bornite by chalcocite; the blue color is due to impurities of iron or cupric copper, as the case may be, left in the chalcocite. Thus, this material is in a transitional form between bornite and chalcocite.

The white areas that cut the bluish areas develop a parallel etching, which suggests that they are pure chalcocite and hypogene in origin. The white areas, by nature of their relationship, are believed to be last to crystallize in the specimen.

Conclusions.—Covellite was formed first and replaced either earlier minerals or gangue. Following this generation and possibly during the same mineralization, bornite with some chalcopyrite was introduced. The mineralizing solutions became impoverished in iron and possibly richer in cuprous copper. The solutions dissolved or replaced the covellite on the one hand, and replaced the bornite on the other. Practically pure cuprous sulphide was deposited last in the form of white chalcocite.

Paragenesis.—Covellite, Bornite-Chalcopyrite, Blue Chalcocite, and White Chalcocite.

DISCUSSION AND SUMMARY OF CHALCOCITE ETCH PATTERNS.

Three types of triangular heat-etch patterns, two parallel types, two mottled and blue types, an irregular type, and an inactive type are discussed and illustrated by photographs. Specimens studied came from the following sources:

Triangular pattern—
- Kennecott, Alaska.....2 specimens
- Butte, Montana.....3 specimens
- Tsumeb, Africa.....2 specimens

Parallel pattern—
- Messina, Africa.....2 specimens
- Roan Antelope, N. Rhodesia, Africa.....2 specimens
- Butte, Montana.....5 specimens
- Globe, Arizona.....4 specimens
- Mufulira, Africa.....8 specimens
- Cornwall, England.....4 specimens
- Langban, Sweden.....1 specimen
- Zinnwald, Saxony.....1 specimen
- Bristol, Conn.....3 specimens
- Tsumeb, Africa.....2 specimens
- Susie Island, Lake Superior.....7 specimens
- Ajo, Arizona.....5 specimens
- Engels, California.....2 specimens

Mottled and Blue pattern—
- Butte, Montana.....4 specimens
- Messina, Africa.....2 specimens
- Globe, Arizona.....5 specimens

Irregular pattern—
- Globe, Arizona.....3 specimens
- Mufulira, Africa.....2 specimens
- Moonta, S. Australia.....1 specimen
- N. Manitoba, Loc.?.....1 specimen

Granular type—
- Butte, Montana.....5 specimens
- Tsumeb, Africa.....1 specimen
- Moonta, S. Australia.....1 specimen
- Globe, Arizona.....4 specimens

Negative—

Replaced wood	4	specimens
Painesdale, Mich.	2	Blue from Covellite.
Globe, Arizona	4	Blue from Bornite.
Ajo, N. Mexico (3)	1	Blue from Covellite.
Sonora, Mexico	1	Blue from Covellite.
W. Pine Co., Nev.	1	Concentric structure.

Possibly all the chalcocite found in the world can be placed somewhere in the given classification for heat-etch patterns.

The following conclusions seem to be suggested by the results mentioned above:

(1) The reaction of the arc-light beam upon the polished surface of chalcocite is due mainly to the effect of heat rays.

(2) The heat-etch pattern is produced by etch lines and fractures that develop along internal structures.

(3) The pattern is characteristic for certain types of chalcocite, and a great deal of the history of the specimen can be inferred from the etch pattern.

(4) Bornite, when replaced by chalcocite under certain conditions will transmit its etch pattern to chalcocite, a conclusion recognized by Graton and Murdock in their original paper.[40]

(5) Covellite in solid solution over a certain percentage in chalcocite will inhibit an etch reaction. In some cases, as in chalcocite from Kennecott, Alaska, enough covellite remained in solid solution in some specimens to preserve the original isometric structure, yet react to the heat of the carbon arc to give an isometric pattern. This indicated that possibly 8 to 10 per cent. covellite was present in the specimen.

(6) Hypogene and supergene chalcocite may be distinguished by comparing their reactions to acid and to heat.

(7) Triangular and parallel heat-etch patterns suggest hypogene origin of the specimen. Mottling possibly represents a transition between bornite and chalcocite. An irregular

[40] Graton, L. C., and Murdock, J.: *Op. cit.*

pattern is caused by extremely fine grains and probably is of supergene origin.

(8) Strains and distorting pressure affecting chalcocite will distort the etch lines. Such a case is readily differentiated from specimens that have not been deformed.

(9) Inactive specimens seem to be of a specialized type and do not offer a drawback to the use of heat etching.

The method of light or heat etching may be applied to the study of many minerals, and the limits of the procedure can be determined only by a prolonged study of polished surfaces.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.,
Nov. 3, 1934.

A HISTORICAL STUDY OF PRECIOUS STONE VALUATION AND PRICES.

SYDNEY H. BALL.

"That which is beautiful is never too costly, nor can anyone pay too much for that which gives pleasure to all," said Abu Inan Farés, Sultan of Morocco, on completion of a beautiful building at Fez. To emphasize his delight, he refused to look at the architect's bill, but tore it up and threw the fragments into the River Fez.

SINCE about 100,000 B.C., man has prized and has desired to possess beautiful stones, and almost from that date he began to offer a rabbit for a bit of chalcedony or a worked flint for a quartz crystal. The earliest gem price known to me, however, dates only from the 4th century before Christ. The musician, Ismenias, purse-proud and ostentatious, heard of an emerald engraved with the figure of the nymph Amymone, obtainable in Cyprus for six gold staters (about $30.65). He sent an agent to purchase the gem, and by shrewd bargaining the latter, returned with it and two of the six staters. Ismenias, with typical musician's temperament, flew into a passion, crying that the agent had ill-treated him by his bargaining and by thus impairing the merit of the stone. Unfortunately, neither is the weight of the stone known, nor the relative value of the material and the engraving. Theophrastus, who lived from 372–287 B.C., states that the carbuncle, in which designation, doubtless, both our garnet and ruby and perhaps our spinel are included, "is extremely valuable, one of a very small size being prized at forty aurei" (about $180). The earliest satisfactory gem prices are those of the Arabian mineralogist, Teifaschi, who in 1150 A.D. ranked the gems as follows: emerald, diamond, ruby and sapphire. He recognized the essential fundamentals of modern gem valuation.

With the exception of radium and a few other very rare elements, the finer precious stones, the diamond, emerald, ruby and sapphire, are the most valuable of all commodities, and their value is concentrated in small weight and bulk. One could conceal a pound of such gems, worth, say, $10,000,000 around his person, and a porter could pack the equivalent of $2,000,000,000 worth of fine gems, except for the fact that such an amount of fine gems could not be procured.

This is a study of the prices of emeralds, rubies and sapphires during the past, and more particularly the last 150 years; it supplements the study of diamond prices made by the writer [1] seven years ago. Deeply colored red, green and blue diamonds, although the most expensive of gems, are not considered here, since they are so rare.

The emerald was known to the Egyptians as early as 2000 B.C.: the sapphire and ruby were first known in Europe to the Etruscans and Greeks between 600 and 480 B.C. The latter gems and the diamond were, however, doubtless known to the Hindoos about 800 B.C.[2]

The value of a precious stone is determined by three main natural characteristics, its beauty (either fire or brilliancy or color), its durability, and its rarity; and a fourth artificial one, the perfection of its cutting, or in the trade, its "make." Minor factors are an adequate supply, its portability, its international market, tariffs, and world economic conditions. These are the factors that determine the value of a fine diamond, ruby, emerald, or sapphire, and in a broad way have made them the most precious of human possessions at least, from the days of Pliny to our own time, a period of some 1900 years. The demand for them is relatively steady and sales are governed by the purchasing power of the world. Fashion, superstition, royal sponsorship, fear of substitution of imitations, nationalistic pride, and effective publicity more specifically affect the less valuable gems.

[1] The Jewelers' Circular, vol. 94, July 27, 1927, pp. 31–35; Eng. and Min. Jour., Aug. 6, 1927.

[2] Ball, Sydney H.: Historical Notes on Gem Mining. Econ. Geol., vol. 26, pp. 681–738, 1931.

Durability is a factor common to the four precious stones here considered, but of course to a higher degree in the diamond than in the sister gems, ruby and sapphire, and to a vastly higher degree than in the emerald. The relative softness of the olivine or peridot, causing it to become scratched if worn in a ring, is one of the factors which lost the gem its former vogue. A diamond, a ruby, or a sapphire is as nearly indestructible as anything in this changing world: time scarcely affects it and fire damages it but little. It is probable that an American of today wears a gem that once graced Charlemagne's court, and hordes of Greek and Roman engraved gems still exist.

Were gems common, they would lose much of their value. I believe, however, that gem owners can face the future complacently: while the unmined supply of diamonds is doubtless adequate, the fields which in the past have supplied us with the best rubies and emeralds are now abandoned or worked only on a very small scale, and the yearly increment to the world's sapphire supply is not large. But more than 200 years after the conquest of Peru, an over-abundant supply ruined the emerald market. Father Joseph de Acosta tells us that when he returned from America in 1587 there were on his ship "two chests of emeralds; every one weighing at the least foure arrobas" (*i.e.* a total of 200 pounds). To show the effect on the price, he states that soon after the conquest a Spaniard in Italy showed a jeweler an emerald "of an excellent lustre and forme: he prized it at a hundred ducats: he then shewed him another greater than it, which he valued at 300 ducats. The Spaniard drunke with this discourse carried him to his lodging, shewing him a casket full. The Italian seeing so great a number of emeralds, sayde unto him, 'Sir, these are well worth a crowne a peece.'" Overproduction has been even more disastrous in the case of a number of semi-precious stones. The enchanting cat's-eye shared its popularity with its meaner sister, the tiger's-eye, which latter was highly esteemed from 1880 to 1890, particularly in America. Tiger's-eye once sold for $6 a carat or even more (say $11,200 a pound), but unfortunately it occurred in quantity on the Orange River,

South Africa. Two speculators, each simultaneously, sent a whole cargo from this locality to London, and the price immediately fell to twenty-five cents a pound. In 1652, a fine amethyst is said to have been as valuable as a diamond, and a relatively high price was maintained until Civil War times, when large imports from Brazil rendered the stone comparatively valueless.

At present the greatest " mine " of gems is that in the hands of the wealthy. Unlike secondary copper, " secondary " gems only return to the market following a complete economic upheaval. The Russians of wealth were Oriental in their love of gems and their shrines were heavy with precious stones. After the revolution, these reached the European and American markets, in part through sales by needy refugees but largely through shipments by the Bolshevik government. It is a tribute to the stability of the gem market that the vast quantities of Russian gems thrown upon it from 1918 to the present time have been absorbed. To heighten the effect, this period coincided with that in which, due to the World War, many European nobles and some kings were forced to dispose of jewels which had been family heirlooms for generations. In normal times, this " mine " is a price stabilizer, for although through financial reverses or death of owners it disgorges a few gems every year, the amount is increased if gem prices become tantalizingly high. While an oversupply of gems is detrimental to the price, an undersupply may also be undesirable. About fifty years ago, the supply of good emeralds was so inadequate that jewel shops frequently displayed few or none, and people turned to other stones more familiar to them. We, who are interested in the diamond, are satisfied that the adequate supply of that gem, guaranteed by large, efficient mining companies, is one factor accounting for its increasing popularity during the past half century.

Political refugees throughout the ages have found the portability of gems valuable, as did that remarkable traveller and business man of 650 years ago, Marco Polo. When he and his uncle returned to Venice in 1295, their relatives failed to recognize these

men garbed in shabby Tartar clothes and almost unable, through long disuse, to speak their native tongue. So the Polos invited their relatives to a stately banquet, and after each course they changed their garments of costly fabrics, the cloth of which was immediately cut and divided among the servants. When the banquet was completed and the servants had retired, Messere Marco brought from a chamber the three travel-stained coats in which the travellers had returned to Venice. With sharp knives, the seams were ripped open and from them came many large rubies, sapphires, garnets, diamonds, and emeralds so artfully concealed as to avert suspicion even if attacked by robbers. Upon quitting the service of the Great Khan of China, they had exchanged their gold for the most precious of gems, knowing that such a quantity of gold could not be transported over a road so long and so difficult. And Gian Battista Ramusio ends the tale with the naïve statement that the relatives " now saw that in spite of all their former doubts, these were really the honored and worthy gentlemen of the Polo family as they had claimed to be, and they therefore paid them the greatest honor and reverence. And when the story became current in Venice, straightway the whole city, gentle and simple, flocked to the house to embrace them, and to make much of them, with every conceivable demonstration of affection and respect."

The prices of precious stones are, and have been for well over 500 years, standardized throughout the civilized world, due to a universal demand for them and to their portability. Vasco da Gama returned to Portugal from his first trip to India in 1499 with few jewels, since he found pearls and jewels very dear there. Somewhat less than two hundred years later, Tavernier states that prices of all fine gems except the diamond, and at times the emerald, are higher in India than in Europe and that most gems should be brought from Europe to India by traders and not purchased there. About 75 years ago even the diamond ceased to be an exception, and today one must be a knowing gem expert to advantageously purchase precious stones in the East. The Eastern potentates to this day are frequent buyers of especially fine gems in competition with the rich of Europe and America. In

1859, while Brazil was still the premier diamond producer of the world, diamonds, according to supply, might well be cheaper in London or Paris than in Rio de Janeiro.

In this day of intensified artificial restrictions to world trade, gem values are affected by duties; one of the recent depressants on the American prices of gems, largely the basis of the curves herewith presented (Fig. 2), was the reduction in July, 1930, of the American duty on cut gems from 20 to 10 per cent. ad valorem.

Naturally, the world price of gems is affected unfavorably by financial panics and major wars. The French in the latter half of the 18th century bought gems to an extravagant degree, and those of the upper classes who were lucky enough to escape from the horrors of the French Revolution found their gems a means of subsistence in their new homes: denuded as was the homeland of diamonds and pearls, the social leaders after the Revolution were forced to be content with cameos and other inexpensive stones. As the United States is the largest purchaser of gems today, its prosperity in the years immediately before 1930, and its lack of excess funds from that date to this, are expressed in the price curves of the principal gems, although the present trend seems stationary and should soon be upward.

The notable increase in per capita wealth during the past fifty years multiplied the number of potential gem buyers. With the consequent increase in the number of wealthy individuals, the demand for large gems has broadened, and in the past two decades has perhaps tended to force down relatively the price of one-carat stones, the unit used in the table, since such stones have been supplanted by larger gems in the finest jewelry.

Fashion is a minor price factor among the finer gems, since they are almost always in fashion. From about 1916 to 1922, however, the ruby was less sought after than normally. On the other hand, the emerald was exceedingly popular in France when Napoleon III was emperor, green being the imperial color. Many of the minor gems, the garnet, amethyst, olivine, and topaz, are, however, much less popular than formerly. Some of us may have forgotten that in the nineties, no American dandy was well-groomed without his cat's-eye.

Superstition plays its part in gem values; for example, the senseless prejudice still held by otherwise sensible people against the glorious opal. In India, flawed or off-color sapphires are considered unlucky, although fine sapphires bring good luck.

Gems have always been considered appropriate votive offerings, and the famous shrines of the Roman Catholic, Greek Catholic, Buddhist and Brahminic faiths in particular are treasure-houses of beautiful gems. The emerald is in considerable demand for ecclesiastical use, as the stone is supposed to symbolize faith; green being one of the liturgical colors, the gem is used on altars and in vestments. The sapphire in the Middle Ages was supposed to cool all human passions, hence its frequent use in bishops' rings.

Royal sponsorship has had its effect on gem prices. Frederick the Great of Prussia was a great admirer of chrysoprase, perhaps because it was mined in territory captured by him in 1745 in the Second Silesian war. His patronage for a time notably increased the prestige of this attractive species of quartz. The stone selected by members of the British royal family to be set in the bride's engagement ring has always gained in popularity, more particularly in the British Empire. We may cite the cat's-eye given Princess Louise of Prussia by the Duke of Connaught (1879); the emerald engagement ring of Viscount Lascelles and Princess Mary (1922); and the sapphire rings of the Duke and Duchess of York (1923) and of the Duke of Kent and Princess Marina (1934).

From the time of the Egyptians, gems have been imitated, but few false gems are perplexing to any but the tyro. In 1890, however, Fremy and Verneuil succeeded in producing synthetic rubies and sapphires, and synthetic rubies began to appear on the market in 1904–5, and sapphires in 1909–10. For a time, the prices of these gems were unsettled; but when it was established, about 1912, that the short-comings of the man-made material could readily be detected by any competent jeweler, the prices of rubies and sapphires continued on their upward course.

Nationalistic sentiment may cause a rare precious stone to be abnormally popular in the land of its origin; the outstanding case

was that of alexandrite in Czarist Russia; in America also the local gems, benitoite, kunzite, hiddenite and tourmaline are more commonly used than elsewhere. Alexandrite was first found in the Urals on the day the Czarevitch, Alexander Nicolajevitch, later Alexander II, became of age. This was enough to render it popular in Russia, but the stone, green by natural, and red by artificial light, combined the colors of the Imperial Guard.

Effective publicity increased the value of gems in the Middle Ages, for in those days the trade was accustomed to exaggerate the perils of obtaining precious stones from the Eastern gem fields: with transportation such as it then was, the perils were enough without multiplying the number of man-eating tigers that waylaid the traveler, without transforming peaceful natives into cannibals, and without introducing a fancy assortment of dragons, gryphons and monstrous serpents. The first tourmaline recognized in Europe was found in 1703 among a package of Ceylonese stones discarded by a Dutch lapidary. The children of the neighborhood were intrigued by the gem's ability to attract light objects, and dubbed it "aschentrecker" or "ash drawer." French and English scientific circles started a furious discussion of this phenomenon, and the socially prominent eagerly sought a piece of tourmaline jewelry. One of Hogarth's paintings shows a gay youth of the day absorbed with the wonders of his tourmaline as he held it in the rays of the sun.

The world has been relatively consistent in its ranking of gems for some 1900 years, for Pliny informs us that after the diamond, "the most costly of human possessions" known "to kings only and to very few of them," the Romans ranked the pearl, then the emerald, and then the opal. He does not give a rating of the ruby and the sapphire. The Five Great Gems of the Hindoos (Maharatnani) from time immemorial have been the diamond, pearl, ruby, emerald and sapphire. In the 13th century, the Persians ranked the diamond after the pearl, ruby, emerald and chrysolite. But the primitive cutting of that day brought out but a small fraction of the diamond's brilliancy and fire.

Figure 1 gives an average for the past seventy-four years of the price graphs of the diamond, emerald, ruby and sapphire with-

out weighing [3] the relative sales volume of the four gems. I have added thereto a curve representing the mean price of representative industrial stocks quoted on the New York Stock Exchange, and likewise a commodity price curve. The upward tendency of the gem prices, together with their relative stability, corroborates the findings of Mr. Lewisohn, a writer in the French magazine "Vu." A listing of the richest men of the world before and

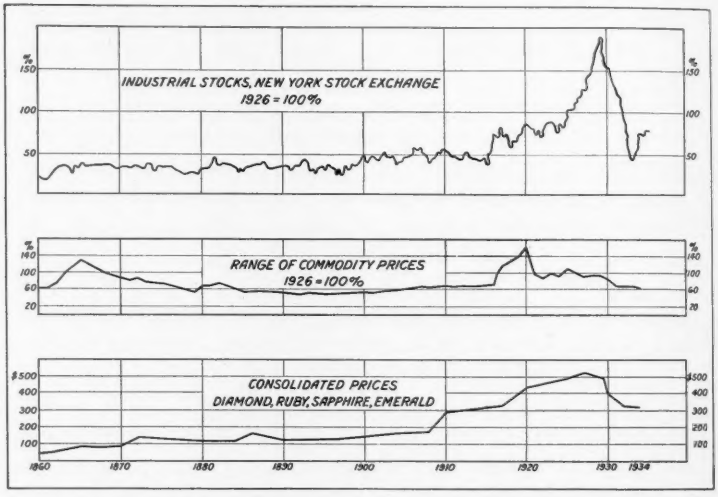

FIG. 1. Graph showing price range of diamond, ruby, sapphire and emerald in comparison with industrial stocks and commodity prices, 1860 to 1934.

after the 1929 panic showed him that the Indian rajahs whose wealth was largely in gold and precious stones had fared much better than American and European multi-millionaires with their wealth in stocks and bonds. This is not, however, set forth as an argument for the investment value of gems, which pay no dividends except those of the constant enjoyment of beauty.

[3] Diamonds sales much exceed those of all other gems combined; accounting as they do for perhaps 95 per cent. of the total.

Further, it should be emphasized that a forced sale of gems in times of financial distress might net but 50 to 70 per cent. of the price at which they were bought, although if given ample time, the jewel broker should be able to dispose of fine gems at prices approximating those given in Figure 2.

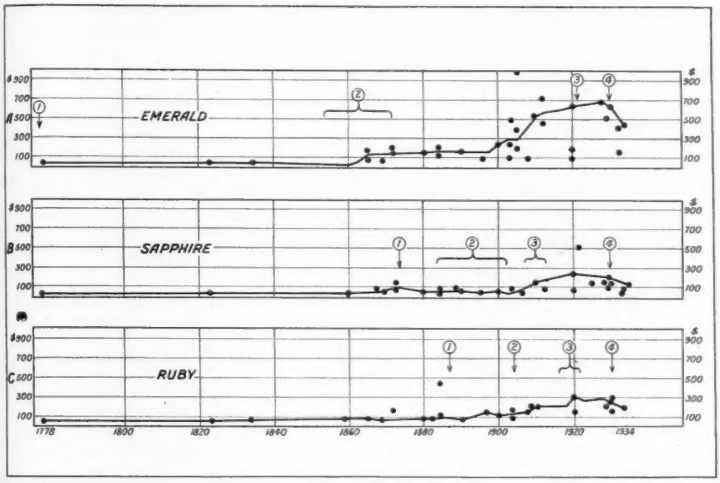

FIG. 2. Prices of precious stones, 1778–1934.

Emerald:—(1) 1567–1800. Market depressed by oversupply of Colombian emeralds. (2) 1852–1871. Very popular under Third Empire (France). (3) Princess Mary's engagement ring-stone, emerald. (4) 1930. American tariff reduced from 20 to 10 per cent ad valorem, emphasizing effect of depression.

Sapphire:—(1) 1871–2. After Franco-Prussian War, became very popular. (2) 1883–1903. Four new fields increase supply greatly. (3) 1909–1910. Synthetic sapphires appear on market; by 1912 adverse effect ended. (4) 1930. American tariff reduced from 20 to 10 per cent. ad valorem, emphasizing effect of depression.

Ruby:—(1) 1887. Burma Ruby Mines Ltd. starts operations. (2) 1904–5. Synthetic rubies appear on market. (3) 1916–22. Ruby temporarily out of vogue. (4) American tariff reduced from 20 to 10 per cent. ad valorem, emphasizing effect of depression.

The prices used in compiling the graphs are to be considered as approximations only of the value of a good one-carat cut stone. In the first place, the authorities depended upon do not in all cases specify the grade of gem priced; and further, in colored gems there is a wide latitude in what two experts consider a fine stone. In a broad way, however, the graphs are believed to present a true picture of changes in gem prices. While a number of early gem prices exist, covering the period from the 12th to the 18th centuries, they are few, and probably refer to stones of such varying grade that it would be of doubtful value to extend the diagram to include them.

From about 26 A.D. to about 1500 A.D., a one-carat white diamond was the most expensive stone; from 1501 to about 1800 the ruby led; from 1801 until 1872 the diamond regained and held the lead, but from the later date to the present day the emerald has been the most expensive stone.

Exceptionally fine gems are so rare that they have no fixed price, and each transaction becomes a matter of negotiation between buyer and seller. As with a fine painting or other work of art, set rules do not hold. Such are red, green, or blue diamonds, white diamonds of unusual size and brilliancy, rubies of over four carats, emeralds of fine deep color and relatively free of flaws, particularly if of good size, and unusually fine sapphires.

The ruby (Fig. 2, C) has always been one of the highest priced gems, alternating with the diamond and emerald for the leadership in one-carat prices, while exceptionally large rubies (3 to 9 carats or more), due to their great rarity, are the most expensive of stones. Such stones bring from $3000 to $7000 a carat. About 1592, Linschoten introduced a rule for the valuation of gems, namely, the value of a stone of more than one-carat is the product of the value of a one-carat stone by the square of the stone's weight. For the past sixty years, this rule has been valueless in diamond valuation, due to the extraordinary number of large stones reaching the market from South Africa. It is still approximately correct in ruby valuation, the resulting price being too high in the case of stones only slightly over a carat and too

low in those of three carats or more. Benevenuto Cellini, in 1558, gave the following figures for a one-carat stone:

Ruby	$779.20
Emerald	389.60
Diamond	48.70
Sapphire	4.87

I infer that the ruby and emerald were exceptionally fine stones, or perhaps Benevenuto, as he sometimes did, was exaggerating a bit. The one-carat ruby continued to be more valuable than the diamond up to the end of the 18th century, but the diamond then passed it and continued higher in price until 1884, when for five years the ruby exceeded it. About 1872, the price of a fine one-carat emerald passed that of both diamond and ruby, and presumably the emerald will in the future retain first place. In gems of two carats or more, however, even in the first eight decades of the 19th century, rubies were more valuable than diamonds. From about 1906 to 1908, the price was slightly depressed by the appearance on the market of synthetic rubies, while from about 1916 to 1922 the stone somewhat lost its vogue. Since the company producing fine rubies, Burma Ruby Mines Ltd., is no longer operating, further advances are likely.

The price of the sapphire (Fig. 2, B) is much below that of the diamond, but Streeter, in 1884, reported that some fine 2 to 3 carat stones were then as valuable as diamonds of the same weight. In the interval from 1880 to 1905, the price decreased due to the bringing into production of four important fields within a period of but twelve years, namely: (1) the beginning of sapphire mining in Queensland in 1881 (discovery 1876, important production not until 1891); (2) the discovery of the Kashmir field in 1882 and (3) that of Phailin, Cambodia, in 1885; and (4) the opening up of the Montana field in 1893 (sapphires first recognized there in 1865). Fine large sapphires are by no means as rare as fine large rubies or emeralds, and in consequence the price increase per carat is by no means as great as in those gems: a ten-carat stone might be worth from 40 to 60 times the value of a one-carat stone.

The emerald (Fig. 2, A) is at present the most precious of all gems; it has always held a high place except from about 1565 to 1790, when the price was depressed by unwieldy exports from South America. The value of an emerald is determined by depth of color, brilliancy and relative freedom from flaws, for flawless emeralds are practically non-existent. Stones of good quality over one-carat, more or less, increase in value by the square of the weight—a generalization true since the 16th century.

26 Beaver Street,
New York City,
March 1, 1935.

THE ORIGIN OF IRON ORES IN SINGHBHUM, INDIA.[1]

J. A. DUNN.

INTRODUCTION.

DURING the last fourteen years several descriptions of the iron-ore deposits of Singhbhum and Orissa have appeared in the Records of the Geological Survey of India and other publications.[2] The most comprehensive of these is the memoir by H. C. Jones, lately published, and recently reviewed in this journal.[3] The present writer, apart from making a brief reference [4] to the trend of his ideas about these deposits in 1925 (published in 1929) has refrained from entering into discussions on the associated problems. Now, however, with the conclusion of the writer's survey of these rocks, extending over several thousand square miles, the final views formed may be advanced.

GENERAL GEOLOGY.

The iron ores of Singhbhum and the Feudatory States of Orissa form part of an Archean group of sedimentary and volcanic rocks known as the Iron-ore system. This system rests unconformably upon the upturned truncated beds of an older group which has been termed the Older Metamorphic system. The names given to these two Archean systems are at least de-

[1] Published with the permission of the Director, Geological Survey of India.

[2] Parsons, E.: Indian Iron Ores. Mining Mag., 26, pp. 9 *et seq.*, 1922. Jones, H. C.: The Iron Ores of Singhbhum and Orissa. Rec. Geol. Surv. Ind., 54, pp. 203–214, 1923; Quinquennial Review of the Mineral Production of India for the years 1924 to 1928. Rec. Geol. Surv. Ind., 64, pp. 111–134, 1930; Mem. Geol. Surv. Ind., 63 (2), 1934. Percival, F. G.: The Iron Ores of Noamundi. Trans. Min. Geol. Inst. Ind., 26 (3), pp. 169–271, 1931; and Discussion, 26 (4).

[3] ECON. GEOL., vol. 30, p. 95.

[4] Dunn, J. A.: The geology of North Singhbhum, including parts of Ranchi and Manbhum Districts. Mem. Geol. Surv. Ind., 54, p. 27, 1929.

scriptive, if not illuminating as to locality, and use of the controversial term Dharwar is avoided.

The Iron-ore system is now divided broadly as follows:

(5) Dalma series of volcanic flows.
(4) Tuffs; flows; shales, phyllites and mica-schists; quartzites and conglomerates.
(3) Shales, phyllites and mica-schists.
(2) Limestones.
(1) Sandstone-conglomerates.

The main series of Dalma flows at the top of the system rests with slight overlap on the tuffs below. A quartzite, with conglomerate at the base, commonly underlies the main flows, and the base of this conglomerate is in places an obvious erosion surface.

Over part of the area, especially in the neighborhood of the principal iron-ore deposits, the rocks have suffered little metamorphism, but elsewhere they merge gradually into highly metamorphosed types, which occupy the larger part of the area. The system has been intruded in turn by ultrabasic igneous rocks, granites, and the latter by immense dolerite dikes.

Iron ore occurs in No. 4 zone, and the larger deposits are generally associated with a rock locally termed *banded hematite-quartzite*. This is a finely banded jasper rock, consisting of alternating bands of hematite, jasper and white cherty quartz, exactly similar to the itabarite of Brazil, the taconite and jaspilite of Lake Superior, and the " calico rock " of South Africa. This rock has been in places metamorphosed to grunerite rock in such deposits as Gorumahisani and Badampahar in Mayurbhanj State. Jones and Percival have described the various types of ore present —shaly porous hematite, massive hematite, and fine powdery hematite. They have described individual deposits and their structure in great detail, and it is not proposed to enter upon a further description here.

ORIGIN OF IRON ORES.

Previous Ideas.—The interpretation of these deposits has hinged upon the origin of the iron oxide and cherty silica in the

finely banded quartzites. Both Percival[5] and Jones[6] accept them as chemical precipitates, deposited most probably under marine conditions—a view that has been postulated for most of these banded quartzites associated with iron ores in other countries. Percival concludes "that the ore bodies are associated genetically with igneous rocks, and the most probable source of the bulk of the ore and the silica was from hot magmatic waters and possibly magmatic vapors ejected under submarine conditions."[7]

Both Percival[8] and Jones[9] regard the porous shaly ore as resulting from enrichment by the leaching of silica originally present.

Percival believed that the powdery ore represents a "chemical precipitate such as might be produced by the sudden chilling of magmatic solutions on their injection in the sea."[10] Jones, however, supplies convincing evidence that it is the pure residue left after the complete removal of silica from laminated hematite, and points out that even the structure of the latter is commonly preserved by the fine powder.[11] More recently, during discussion in the field, Percival personally intimated his acceptance of this latter view.

According to Percival, the massive ore is an original deposit.[12] Jones, on the contrary, supplies uncontrovertible evidence indicating that its origin is due to local enrichment by removal of fine silica from the banded hematite-quartzites; in rare instances it is an enrichment by further deposition of hematite, especially in shales.[13]

This paper is concerned with the original mode of deposition of these beds, and the ultimate source of the iron, and not with

[5] Percival, F. G.: *Op. cit.*, p. 226.
[6] Jones, H. C.: Mem. Geol. Surv. Ind., 63 (2), p. 199, 1934.
[7] Percival, F. G.: *Op. cit.*, p. 239.
[8] *Idem.*, p. 250.
[9] Jones, H. C.: *Op. cit.*, p. 243.
[10] Percival, F. G.: *Op. cit.*, p. 245.
[11] Jones, H. C.: *Op. cit.*, p. 245.
[12] Percival, F. G.: *Op. cit.*, p. 242.
[13] Jones, H. C.: *Op. cit.*, p. 244.

the origin of the individual ores. The writer, however, agrees entirely with the above conclusions of Jones on this latter question.

Associated Volcanic Rocks.

All previous writers on this area have, of necessity, gleaned their information from the immediate neighborhood of the large iron-ore deposits. The present writer, however, has had the good fortune to survey the rocks of the Iron-ore system over a wide area, during a period of over twelve years. His study has forced him to certain conclusions which are found to hold throughout the area and not merely in the principal deposits.

The first point which has emerged from the writer's survey is that these iron-ore deposits are associated with a zone that consists almost entirely of metamorphosed volcanic tuffs and occasional lava flows, as can be demonstrated in many places. The tuffs vary from extremely fine-grained shaly or phyllitic rocks (frequently indistinguishable from normal sediments) to tuffs whose origin can be determined with the naked eye. Commonly these phyllites consist entirely of chlorite; in places they contain abundant carbon; generally the phyllitic type contains much magnetite and the shaly type, abundant fine hematite.

Any explanation of the origin of the iron-ore deposits must take cognizance of the rocks with which they are so definitely and without exception associated—the tuffs.

Banded Hematite-Quartzite and Iron Ore.

In descriptions of the deposits the banded hematite-quartzites take a major place. A wider survey, however, shows that these quartzites are by no means unique, and that they are not primary sedimentary rocks. They are due to the silicification of other rocks now represented by ferruginous shales and phyllites. Such silicification has not been peculiar to the ferruginous phyllites; carbon phyllites in places vary to a massive black quartzite or a black, gray, and white banded rock; chloritic phyllites less commonly grade either to a massive green chert or to a green and

white banded rock; sericitic phyllites merge into a gray cherty rock either banded or massive, and even the lavas themselves have occasionally been silicified. In all these varieties the nature of the original rock is indicated by unreplaced material which can be observed under the microscope. In the field a normal phyllite can commonly be traced along the strike into a banded quartzite. Hence, so far as the silica in these quartzites is concerned, any theory of marine precipitation is discounted. The banding in these rocks is not phenomenal; it is precisely what might be expected where replacement has taken place along and inwards from fine bedding planes, and is by no means an uncommon feature of replacement. Any supposed uniqueness is merely a matter of size.

Although the banded hematite-quartzites are certainly secondary, there are quartzites of undoubted sedimentary origin interbedded with the phyllites in the zone of tuffs, and even conglomerates are found. The latter suggest, not marine conditions, but fluviatile or lacustrine; in fact, conglomerates in places rest on locally eroded lavas. The lava flows show no sign of ellipsoidal structure such as might be present if they were poured out over a sea bottom, and indeed, in the whole area there is nothing to suggest that this zone of tuffs, lavas, quartzites and conglomerates was formed under marine conditions. In places where conglomeratic quartzites intervene between the zone of tuffs and the main flows above, the top of the tuffs is an obvious horizon of Archean weathering. The evidence points to the prevalence of subaerial conditions.

The picture then clears itself—a thick series of fine tuffs with some intercalated sandy beds and lava flows, formed mainly under subaerial conditions, replaced at a few points to give rise to banded quartzites of various types, and iron ores.

Source of Iron.

A study of the chloritic phyllites indicates that they are extremely high in iron, in the form of magnetite as well as chlorite. Frequently, as these chloritic phyllites are traced laterally along

the strike, both chlorite and magnetite are seen to give place to hematite, eventually merging into a hematite-phyllite, hematite-schist, and even iron ore. Again and again this association of hematite-phyllite with chloritic phyllite can be demonstrated, forcing the conclusion that the large areas of hematite-shales and hematite-phyllites are merely another form of the chloritic phyllites, completely oxidized.

It is, of course, obvious that this alteration of chloritic phyllite to hematite-schist is Archean, or at least it must have taken place prior to silicification and formation of the banded hematite-quartzite. Some of the deposits occur as roof pendants in the granite, and the silicification was pre-granite.

It is possible to fix with fair exactitude the latest period during which silicification has taken place. Fermor [14] has shown that chertification along the margins of ultrabasic intrusive rocks in Singhbhum was pre-granite in age. Extending the area over which these rocks occur, the writer has noted that the banded hematite-quartzites were formed at approximately this same period. Furthermore, it now appears that these ultrabasic rocks are an intrusive phase which accompanied and continued after the extrusions of lava flows. Silicification of the phyllitic tuffs apparently took place, then, not long after their formation. It follows that hematite must have replaced chlorite during the formation of the series or immediately afterwards.

There are instances in several parts of Singhbhum of alteration of the lavas to clay, generally ferruginous. Such clay has been subjected to all the movements of the rest of the system, and has given rise to ferruginous shales and phyllites in which small almost unaltered kernels of lava can be seen in places, just as in altered Tertiary lavas. Contemporaneous surface alteration of the lavas during Archean times was a fact, and it does not need any considerable widening of the field of view to embrace the fine tuffs also in this alteration.

The association of sandstones and conglomerates indicates that normal sedimentation was also going on, probably within lakes

[14] Fermor, L. L.: General Report for 1918, Rec. Geol. Surv. Ind., 50, p. 10, 1919.

and river valleys. Occasionally hematite-schists are found to be interbedded with such true sediments, and the inference is that they were brought in as a wash from adjacent decomposed tuffs and lavas. Many of the pebbles in the interbedded conglomerates are lithologically identical with adjacent beds; pebbles of banded jasper quartzite are common in them, so that obviously silicification must have taken place contemporaneously with deposition.

It is not certain whether all this oxidation of the volcanic series resulted from surface alteration in Archean times. There are many examples reminiscent of alteration under thermal conditions, similar to those prevalent in such an area as the thermal region of New Zealand; even a form of siliceous sinter has in places been observed.

Conditions of Accumulation.

The picture now emerges of a thick terrestrial group of fine tuffs and flows being gradually built up, exposed throughout to atmospheric conditions of alteration over a prolonged period of time. In depressions and lakes on the surface occasional sediments were deposited, in places a ferruginous wash from the surrounding volcanic rocks, to be later covered by fresh falls of tuff and outbursts of lava. Many of these early flows were completely decomposed and gave rise to ferruginous clays, an alteration which was assisted possibly by thermal waters. Thermal activity, prevalent throughout the accumulation of these tuffs and flows, gave rise to contemporaneous silicification and the formation of banded quartzites. Denudation was active over this land surface and the debris from many of the newly formed banded quartzites gave rise to interbedded conglomerates.

Eventually the whole series was covered by the final outpouring of lavas, aggregating over 2,000 feet, which followed each other in such rapid succession that interbedded tuffs rarely accumulated. Extrusion of lavas ceased, but intrusion of gabbros and ultrabasic rocks into the series below continued until long afterwards.

These later stages were accompanied by widespread silicification, continuing the development of the banded quartzites. Much of

the rearrangement of iron oxide with enrichment in certain places may have taken place at this period. A large part of the silica in the banded quartzites may not be magmatic, but was perhaps derived from the adjacent rocks as the solutions permeated through them. Such removal of silica in certain cases may have given rise to porous ore. In other cases it gave rise to a highly aluminous shale.

Discussing Percival's paper on the iron-ores of Noamundi, Spencer [15] referred to the high alumina content of some of the shales associated with the iron ore in the tuff zone. He also described instances of intensive leaching of the shales immediately underlying the banded hematite-quartzites (considered by Percival to be tuffs); small pockets are of almost pure kaolin. Such leaching is typical of thermal regions, and in Singhbhum was an important feature during iron-ore deposition.

These highly aluminous beds throw further light on another subject. The writer has long known that the kyanite deposits of Singhbhum belong to the same zone of tuffs as do the iron ores. Up to the present he has regarded them as derived from highly aluminous clays, possibly in part bauxitic, due to Archean alteration of tuffs. Much of this alteration now appears to have been due to leaching under Archean thermal activity. This explanation is in keeping with the peculiar discontinuous and lens-like nature of many of the kyanite masses, and also explains the amazing purity of some of the mica schists with which the kyanite is associated.

Similar Deposits in Other Regions.

Descriptions of these banded quartzites in different parts of the world give prominence to the occurrence in them of carbonate rhombohedra (in general apparently siderite) which have been replaced, leaving merely quartz pseudomorphs with a little iron oxide. Singhbhum is no exception to the occurrence of these pseudomorphs, but they are not confined to the banded hematite-quartzites. Rhombohedra of dolomite and siderite (possibly

[15] Spencer, E.: Trans. Min. Geol. Inst. Ind., 24 (4), p. 324, 1932.

ankerite) are common in the chloritic phyllites and other tuffs and in the typical associated cherts; pseudomorphs of them are commonly preserved in the various banded quartzites—banded chloritic quartzites, banded carbon quartzites, and banded hematite-quartzites. These carbonate crystals obviously preceded silicification and were formed during an early stage of thermal activity. They have no particular significance, such as being the original source of the iron in the ore deposits; in tuffs already high in iron the formation of siderite by permeating CO_2 as well as of dolomite, might be expected. The dolomitic limestones adjacent to the iron-ore deposits are probably secondary and formed at this stage.

Van Hise and Leith [16] in 1911 suggested that the iron and silica of the Lake Superior ores were formed partly by magmatic waters and perhaps in part by the reaction of sea-water upon hot lavas. Gruner [17] calculated that if the silica were derived from magmatic springs the quantities of water required could be furnished only by an incredibly large magma. This might be so if *all* the water in a thermal region were of direct magmatic origin. Anyone acquainted with thermal regions is aware, however, that by far the greater proportion of water emitted by hot thermal springs is meteoric, and has become superheated by ascending magmatic steam. Frequently the investigator can amuse himself by controlling the surface water from which an adjacent geyser draws its supply. In such an area underground circulation with its concomitants of leaching and transportation of minerals, must be at a maximum and capable of moving immense quantities of silica. The thermal theory of the origin of the banded quartzites has no difficulties in respect of the amount of water required. Under submarine conditions the water available is, of course, vastly greater than under sub-aerial.

The arguments advanced, postulating organic and chemical precipitation of the iron and silica in these formations, have been

[16] Van Hise, C. R., and Leith, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Surv. Mon., 52, 1911.

[17] Gruner, J. W.: The Origin of Sedimentary Iron Formation. ECON. GEOL., 17, p. 448, 1922.

published so frequently that it is unnecessary to recapitulate them. Moore and Maynard[18] have tackled the question in greater detail than any previous workers, and their experiments on solution, transport and precipitation of silica are the most authoritative to date. They conclude that the large areas of pre-Cambrian igneous rocks are the source of the iron and silica which went to build up the Lake Superior deposits; that the iron was

> dissolved and carried as a ferric oxide hydrosol and the silica as colloidal silica, the two being stabilized by organic matter which kept them from mutually precipitating one another until thrown down by electrolytes in the sea. . . . [Banding was probably] due to the differential rate of precipitation of the iron and silica combined with the influence of seasonal changes causing varying quantities of these substances to be brought into the basin of deposition at different periods throughout the year.[19]

Notwithstanding all this, the senior writer had to point out that

> hot waters have played a more important rôle in the deposition of the highly siliceous formations associated with igneous rocks than was formerly admitted. . . . The detailed work by Collins in the Michipicoten area has led him to advocate a hot spring origin for the banded silica and a replacement origin for the carbonate and pyrite in the area,

and other instances of similar replacement deposits are mentioned.[20] Although he maintains that the "banding in the highly siliceous iron deposits is undoubtedly original and due to chemical deposition," he admits that the only thing approaching these highly siliceous banded deposits of the pre-Cambrian era forming today "is found around hot springs and in association with igneous rocks."

Although most of those who have investigated these deposits have pointed out that there has been a rearrangement of the iron and silica in the banded hematite-quartzites, few would admit a completely secondary origin for them. Usually the extraordi-

[18] Moore, E. S., and Maynard, J. E. Solution, transportation and precipitation of iron and silica. ECON. GEOL., 24, pp. 272–303, 365–402, 506–527, 1929.

[19] Ibid., p. 524.

[20] Ibid., pp. 525–526.

narily even nature of the banding has been accepted as indicating their sedimentary origin. Irregularities, such as rapid thickening and complete thinning out of bands, and "ghost" bands are regarded as due to secondary rearrangement. All the banded hematite-quartzites that the writer has examined show a much greater irregularity of banding than appears at first glance, and indeed there is more sign of replacement than there is suggestion of bedding. It seems from the literature that this supposed regularity of banding has been responsible for the implicit acceptance of these rocks as sedimentary.

There seems also to be an opinion among several writers that banded rocks of this nature are confined to the Archean era, but this is not entirely correct. Although banded hematite rocks are not a feature of later periods, the other siliceous banded varieties described do occur. Mr. Auden informs me that in the area of the lower Himalaya north of Mussoorie he has mapped a thickness totalling 5,000 feet of interbedded coarse tuffs and banded fine tuffs which he describes as quartzite-phyllites. These are provisionally called the Chandpur stage of the Jaunsar series, probably older Paleozoic (Devonian) in age. Specimens of these quartzite-phyllites which Mr. Auden has shown me are similar to many of the banded rocks of Singhbhum.

CONCLUSIONS.

The immediate neighborhood of the larger iron-ore deposits in Singhbhum provides little evidence to support any theory of their origin. A wider survey over several thousand miles of country demonstrates that the associated banded quartzites are not sedimentary, but are due to secondary silicification of material now represented by ferruginous, chloritic or carbon shales or phyllites, many of which originated as tuffs. Other theories advanced to date are untenable in Singhbhum.

It is believed that this silicification was in part contemporaneous with deposition of the beds, and resulted from thermal activity accompanying the formation of the volcanic series. The iron was in part derived from the oxidation of tuffs and flows *in situ*,

and in part represents a wash from the latter. Later solutions have rearranged the ferruginous content, to give the massive iron ores. The series was built up slowly, and in intervals of denudation occasional conglomerates accumulated, with pebbles shed from adjacent, already formed, banded quartzites and other rocks.

GEOLOGICAL SURVEY OF INDIA,
CALCUTTA,
Nov. 23, 1934.

GEOLOGICAL SIGNIFICANCE OF MAGNETIC PROPERTIES OF MINERALS.[1]

C. W. DAVIS.

INTRODUCTION.

PAST attempts to classify minerals by their magnetic properties and to correlate these properties with the geologic origin of their ores have been handicapped by the meager knowledge of the nature of the ferromagnetism of minerals and by a lack of suitable methods and apparatus for the quantitative determination of the magnetic properties of mineral powders.

Work recently completed by the mineral physics section of the Metallurgical Division of the U. S. Bureau of Mines has developed methods and apparatus of demonstrated merit. As a result, some progress has been made in the accumulation of quantitative data on the magnetic properties of natural and treated minerals as exhibited by hysteresis loops of such material, and evidence has been contributed relative to the nature of ferromagnetism.[2] This permits the presentation of geologically significant results, including a discussion of the nature of lodestone and of hydrated iron oxides, and indicates the possibility of a classification based mainly on magnetic properties that may have diagnostic value with respect to ore genesis.

THE NATURE OF LODESTONE.

An answer to the long-standing question of what and why is a lodestone may be supplied by a consideration of our present concept of the relation of magnetic properties to the chemical and physical constitution of ferromagnetic minerals. This concept

[1] Published by permission of the Director, U. S. Bureau of Mines. (Not subject to copyright.)

[2] Dean, R. S., *et al.*: U. S. Bur. Mines, Progress Reports, Metallurgical Division, 10. Mineral Physics Studies. Rept. of Inves. 3268, 1935.

indicates that magnetic susceptibility is controlled by the kind and amount of magnetic substance present, while magnetic remanence and coercive force are mainly concerned with interfacial surface or secondary structure; it shows further that magnetic properties of minerals may be greatly changed through the agency of heat or other treatment that may affect either the kind or structure of magnetic material present.[3]

The selection of lodestone as a special variety of magnetite is natural, but an examination of its intrinsic properties shows that such a classification is basically unsound. The usual definition that a lodestone is a variety of magnetite having a high remanence, and the additional observation that it generally contains or is associated with oxidation products of Fe_3O_4,[4] are dependent on apparent or accidental rather than on real or fixed properties. The small significance of chemical composition, which is mainly concerned with magnetic susceptibility, is shown by the fact that practically all magnetites with widely different compositions have sufficient susceptibility for classification as lodestones, and the inadequacy of remanence as a criterion for lodestone is disclosed by the fact that some magnetites which have no appreciable attraction for ferromagnetic substances such as soft iron may be converted into " lodestones " with strong magnetic attraction and with a remanence as high as natural lodestones, by the action of a moderately strong unidirectional magnetic field (field strength of about 3000 oersted). The magnetic attraction of lodestones when first magnetized was doubtless much higher than at present, since time, temperature, and mechanical shocks all affect this property.

The tenacity with which magnetism is retained is determined by the magnetic property, coercive force, so that if this property be low, demagnetization will soon take place. Lodestones, therefore, must necessarily have high coercive force, a point that has received too little attention in previous discussions; but some

[3] Dean, R. S., Gottschalk, V. H., and Davis, C. W.: Magnetic Separation of Minerals. U. S. Bur. Mines, Rept. of Inves. 3223, pp. 3–13, 1934.

[4] Newhouse, W. H.: The Identity and Genesis of Lodestone Magnetite. ECON. GEOL., vol. 24, pp. 62–67, 1929.

magnetites with high coercive forces may not have been submitted to proper conditions for magnetization, or if so exposed, may have become demagnetized later. The coercive forces of a few fairly strong lodestones, at a field strength of 2700 oersted and at a packing density of about 2.3 g. per c.c., range from 140 to 270 oersted, while the coercive forces of some natural and artificial (prepared by the gaseous reduction of hematite) magnetites under similar conditions are from 150 to 425 oersted. The latter substances showed no appreciable magnetic attraction before placing in the magnetic field, but after removal from a field of 2,700 oersted became very strong "lodestones."

The accidental nature of the mode of lodestone magnetization is definitely shown by the compilations of Ambronn.[5] Of the various possible suggested causes, such as vibrations caused by violent earthquakes, abnormal earth currents, strong magnetic storms, strong polar lights, cooling in the earth's field, and lightning, the last two are considered of most significance and are substantiated by experimental evidence. Rocks of plutonic origin could have been magnetized by the earth's field while passing through their Curie's inversion point, while various individual blocks of rocks with irregularly distributed polarity were probably magnetized by flashes of lightning. A magnetite that has been exposed to one of the above conditions will not have become a lodestone unless its coercive force is high. This is shown in the case of Ural Mountain magnetite and of the magnetite from an artificial slag, which, although of high susceptibilities, are very low in coercive force and therefore lose their magnetism rapidly. Lodestones may be artificially prepared by magnetizing products resulting from heating hematite in a reducing atmosphere to form Fe_3O_4, with large interfacial surface and consequent high coercive force, or by the heat treatment of many low coercive-force magnetites, especially those containing dissolved impurities such as TiO_2.

It is thus seen that the variable composition and the accidental

[5] Ambronn, Richard: Translation by M. C. Cobb, Elements of Geophysics, pp. 95–96. New York, 1928.

nature of the manner and degree of magnetization prevent lodestone, as such, from having any genetic significance.

THE NATURE OF HYDRATED IRON OXIDES.

Goethite and lepidocrocite have the same chemical composition ($Fe_2O_3 \cdot H_2O$) and both are listed as orthorhombic. By dehydration at 350° to 400° C., however, goethite changes to the ordinary alpha Fe_2O_3, while lepidocrocite becomes the ferromagnetic gamma Fe_2O_3.[6] Herroun and Wilson[7] suggested that the common association of manganese with lepidocrocite (their samples contained about 3.5 per cent. Mn_2O_3) might account for this difference, but other investigators working with artificial compounds came to the conclusion that gamma hydrate produces gamma Fe_2O_3 on heating at 250° to 300° C., while alpha hydrate always produces alpha Fe_2O_3.[8] Heating gamma Fe_2O_3 at higher temperatures causes its reversion to ordinary Fe_2O_3.

Still others found that if the lower iron oxide hydrates are oxidized at low temperatures the gamma hydrate is formed, and that the gamma form is favored by the presence of certain organic nitrogen-containing compounds.[9]

Quantitative determinations of the magnetic properties of a sample of purified lepidocrocite containing 0.21 per cent. MnO showed that heating at 370° C. increased its intensity of magnetization ($4\pi I$), at a field strength of 2,700 oersted and at a packing density of 1.774 g. per c.c., from less than 12 gauss to 414 gauss, while its remanence had become 85 gauss and its coercive force 43 oersted. The dehydrated sample contained no ferrous iron, as determined by decomposition with sulphuric acid (2 : 1) in an atmosphere of CO_2 and $KMnO_4$ titration.

[6] Sosman, R. B., and Posnjak, E.: Ferromagnetic Fe_2O_3, Artificial and Natural. Jour. Wash. Acad. of Sci., vol. 15, p. 329, 1925.

[7] Herroun, E. F., and Wilson, E.: Ferromagnetic Ferric Oxide. Proc. Phys. Soc., vol. 41, pp. 100–111, 1928–29.

[8] Welo, Lars A., and Baudisch, O.: The Two-Stage Transformation of Magnetite into Hematite. Phil. Mag. (London), vol. 50, pp. 399–408, 1925.

[9] Mellor, J. W.: Comprehensive Treatise on Inorganic and Theoretical Chemistry, vol. 13, pp. 780–781. New York, 1934.

From these results it is evident that high coercive force and remanence are characteristic of ferric oxide formed by dehydration of lepidocrocite. Qualitative tests indicate that the same is true for gamma ferric oxide formed by other methods. The gamma form would therefore seem to be stable only when associated with large interfacial surface such as would be exhibited by a very fine state of subdivision.

DIAGNOSTIC POSSIBILITIES OF MAGNETITES.

The wide distribution of magnetite throughout all kinds of formations furnishes a large field of usefulness for methods that will accomplish its classification. New possibilities resulting from new methods and apparatus therefore warrant further work to determine the diagnostic value of the magnetic properties of magnetite.

Chemical analyses have shown that crystals of Ural Mountain magnetite and magnetite crystals separated from a copper reverberatory slag are high in Fe_3O_4, containing about 97.7 per cent. and 95 per cent. respectively. Pure magnetite samples also have a higher intensity of magnetization and a lower coercive force and remanence than other magnetites studied. At a field strength of 2,700 oersted and with a packing density of Fe_3O_4 of 2.705 g. per c.c., and at particle sizes greater than 300-mesh 4π I, coercive force and remanence for Ural Mountain magnetite are 2848 gauss, 6.2 oersted and 52 gauss; for the slag magnetite, 2709 gauss, 4 oersted and 28 gauss; and for an impure magnetite under similar conditions, 1727 gauss, 142 oersted and 490 gauss.

This indicates the possibility that magmatic origin may be divulged by the presence of pure magnetic crystals. In the rare cases where these crystals are sufficiently large and well formed, their magnetic properties may be determined by the method of Weiss,[10] but where the crystals are small or shattered it is necessary to use methods suited to powdered material. A recently developed method of this type takes account of important previously neglected factors, so that the results obtained, although not

[10] Weiss, Pierre: Thesis, Paris, 1896.

absolute values of the solid material, are strictly comparable and reproducible and are given in absolute units.[11]

One important feature of this method is that all three magnetic properties, susceptibility, remanence and coercive force, can be obtained for field strengths surpassing 3000 oersted if our type of apparatus be used.[12]

Preliminary treatment of ore samples containing magnetite for magnetic measurements consists in crushing to liberate the magnetite and separation to remove it. In addition to the usual methods of separation and purification, A. C. magnetic separation is found to be helpful in removing one type of magnetic material from another.[13]

The new method of determination, assisted by careful chemical analysis, provides a means for a more complete study of the nature of magnetites and may lead to a useful classification when samples from all known sources have been examined. Such a conclusion is reached from the fact that the formation of various types of ore deposits was accomplished in different ways and under different conditions and may have been accompanied by characteristic mineral structures with characteristic magnetic properties, especially remanence and coercive force, which are mainly dependent on structure.

The properties of magnetites were apparently developed and modified by the action of heat and by the presence of certain elements or compounds.

Although the value of magnetic properties of natural magnetites in conjunction with chemical and any other determinable properties must yet be ascertained, the diagnostic value of the magnetic properties developed or altered by heat treatment has already been established to a certain extent. Loewinson-Lessing [14]

[11] Gottschalk, V. H., and Wartman, F. S.: Magnetization Curves for Magnetite Powders. U. S. Bur. Mines, Rept. of Inves. 3268, 1935.

[12] Gottschalk, V. H., and Davis, C. W.: An Apparatus for Determining the Magnetic Constants of Mineral Powders. U. S. Bur. Mines, Rept. of Inves. 3268, 1935.

[13] Davis, C. W.: Practical Aspects of A. C. Magnetic Separation. U. S. Bur. Mines, Rept. of Inves. 3268, 1935.

[14] Loewinson-Lessing, von F.: Centralblatt f. Mineralogie, Ser. A, 1932, pp. 369–377.

determined the remanence of magnetites that had been heated at different temperatures and cooled in the earth's magnetic field, and found that different types of curves were obtained for different geologic origins when remanence was plotted against temperature of heating. Magmatic rocks showed sharp maximums at about 700° and 900° C., with minimums at 800°. Contact-metamorphic magnetites gave no definite pattern, but hydrothermal magnetites were characterized by a minimum at 400° C. He recognized the effect of titanium, since magmatic magnetites containing 6.46 per cent. TiO_2 showed a maximum at 600° and a minimum at 700°, while other magnetites with 7.4 per cent. TiO_2 showed gradual changes with temperature.

Material undergoing heat treatment should be examined carefully for interfering substances.

Our information is meager concerning what substances, in addition to titanium, may form solid solutions with Fe_3O_4 and produce a two-phase system of large interfacial area on heat treatment, but we do know that ferrite formation may produce magnetic material. Oxides or carbonates of ferrite-forming mixtures, such as those containing an iron compound together with compounds of copper, manganese, nickel, cobalt, zinc or magnesium, react when the conditions of mixing and heating are correct and form ferromagnetic compounds.

It would seem therefore that the method and apparatus now available for the quantitative determination of the magnetic properties of mineral powders and the information concerning the nature of the magnetism in natural and heat-treated minerals might well be combined with other determinable quantities such as chemical and structural composition, and utilized in a fresh attempt to establish a relationship between the magnetic properties of minerals and the geological occurrence of their ores.

SUMMARY AND CONCLUSIONS.

1. Lodestones are of variable composition, and the manner and degree of their magnetization is accidental; hence their actual magnetic properties show little relation to their present state of magnetization (" residual remanence ").

2. Many natural and artificial magnetites, if their coercive forces and remanences are sufficiently great, will, after magnetization, simulate lodestones.

3. Ferric oxides formed by regulated dehydration of gamma ferric-oxide hydrate, exemplified by lepidocrocite, are strongly ferromagnetic and have high coercive force and remanence, while alpha ferric-oxide hydrate, of which goethite is representative, forms ordinary ferric oxide on dehydration.

4. The diagnostic possibilities of magnetites for ore genesis are discussed, evidence being given to show that new methods and apparatus for the determination of magnetic properties of mineral powders and a new interpretation of the nature of the magnetism of minerals should provide an impetus to investigations seeking to establish a relationship between the magnetic properties of minerals and the geological occurrence of their ores.

METALLURGICAL DIVISION, U. S. BUREAU OF MINES,
WASHINGTON, D. C.,
Sept. 27, 1934.

PARAGENESIS OF THE COLORADA COPPER SULPHIDES, CANANEA, MEXICO.

VINCENT C. KELLEY.

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SUMMARY.

The Colorada ore body is located within and along the contacts of a quartz porphyry stock that has been intruded into a series of massive, fine-grained, volcanic rocks, called the Henrietta formation. The ore body lies some seven or eight hundred feet beneath the present erosion surface which apically truncates the irregular stock. Roughly, the ore body has the form of an inverted hollow cone or crucible with a gash or split on its northeast side.

The early gangue minerals form an irregular, pegmatitic ring-dike, and the succeeding sulphide mineralization is localized within and along the pegmatite ring. The ore minerals are composed chiefly of copper sulphides, molybdenite, and sulpho-salts of copper, principally luzonite and tennantite. All the minerals are of hypogene origin with the exception of minor quantities of "sooty" chalcocite in the upper levels of the mine.

Blue chalcocite and covellite replace an earlier chalcopyrite and bornite intergrowth, the bornite being much more susceptible to replacement than

the chalcopyrite. The textures of the chalcocite and covellite are particularly described in this paper, and the opinion is reached that these textures were formed by hypogene replacement, although it is admitted that some unmixing may have taken place. Deposition of chalcocite and covellite was followed by a later sulphide replacement, represented chiefly by luzonite and tennantite. Alunite is rather abundant throughout the ore body, and its close association with luzonite and tennantite is thought to indicate that these sulpho-salts were carried and deposited by solutions of acid character.

The presence of both blue and gray chalcocite separated widely in the sequence of minerals leaves little doubt as to the distinction of these varieties at Cananea. In general the paragenesis of the minerals of the Colorada ore body is rather unusual and presents several new features with respect to assemblages and sequence. In structure and origin, the ore body is unique and invites special and intensive study, which has been undertaken by V. D. Perry.[1]

INTRODUCTION.

THE study of the paragenesis of the minerals of the Colorada ore body was suggested by Professor F. L. Ransome. A preliminary examination of the textural relations was made on a suite of ores collected for the California Institute of Technology at an earlier date. The results obtained seemed to warrant a more thorough investigation of the ore and its occurrence. Accordingly, with the generous aid of Dr. L. D. Ricketts, the mine was visited in the spring of 1933, and a more complete suite of ores was collected. The purpose of this paper is to discuss the mode of origin of the minerals and their textures with special emphasis upon the chalcocite and covellite relations.

GEOLOGICAL SETTING.

The Colorada mine is near the head of Democrata gulch, on the northeast slope of the Cananea Range, which lies just south of the Mexican border, between Nogales and Naco, Arizona, and has the same general northwest-southeast trend as the Basin Ranges of Arizona and Nevada. The mountain crests have elevations of nearly 8,000 feet and rise some 3,000 feet above the mesa country to the east.

[1] Perry, V. D.: Applied Geology at Cananea, Sonora. Ore Deposits of the Western States, p. 701. A. I. M. M. E., New York, 1933.

The rocks of the region consist of remnants of Paleozoic quartzites and limestones, unconformably overlain by an immense thickness of volcanic rocks which are divisible by unconformities into three series, the Elenita, Henrietta, and Mesa formations. The Paleozoic and volcanic rocks are intruded by several deep-seated differentiates, of which quartz porphyry appears to be the youngest. These intrusive rocks form belts that lie along the northeast flank of the range, roughly parallel with its axis.

THE COLORADA ORE BODY

At the Colorada mine the latest of the granitic differentiates, known as the Colorada quartz porphyry, forms an irregular, nearly vertical stock in the Henrietta formation. Within the stock are two brecciation pipes, and the Colorada ore body is included in the smaller and younger of these.

The ore body was discovered in 1926, during the progress of drilling to determine the limits of low-grade disseminated mineralization in the Democrata Gulch area. Except for small sporadic areas of tourmalinization and brecciation and only slight increase in the number and size of quartz and iron-oxide veinlets, the deposit had no surface expression. The top of the ore body is some seven or eight hundred feet below the present erosion surface, which truncates the irregular apex of the stock. Consequently there are no extensive enriched masses of either oxidized or secondary-sulphide minerals. However, weak manifestations of primary mineralization extending above the central ore mass are indicated by disseminated secondary sulphides and oxidized material, averaging from one to one and one-half per cent. of copper, above the high-grade ore body.

The upper rim of the ore body terminates rather irregularly between the fifth and sixth levels. From the sixth to the ninth levels the plan of the ore body roughly resembles a horseshoe. Below the ninth level the horseshoe shape thickens centripetally, until on the tenth level the entire circle is ore. The annular portion, above the solid base, has three concentric units. The outer unit is pegmatitic, and is composed essentially of quartz, phlogo-

pite mica, and some feldspar, with the last two minerals more prominent near the outside of the ring. Quartz increases in proportion to mica upward in the dike, and the mica crystals decrease in size, so that in the upper portions the aggregate is more nearly aplitic in contrast with the pegmatite on the lower levels. The second structural unit lies just inside of the pegmatite shell and is composed primarily of sulphides, which penetrate and replace the enclosing pegmatite along fractures. The third structural unit is the brecciated core, the shattering of which took place after the bulk of the sulphide deposition. The brecciation is normally inside of the sulphide shell, but in places it has involved the sulphides and parts of the pegmatite. It is typically composed of fragments of sulphide, quartz, and quartz porphyry up to two or three feet in diameter, in a squeezed groundmass of finely pulverized clastic material.

GENERAL CHARACTER OF THE ORE.

The massive sulphide aggregates are composed chiefly of chalcopyrite, bornite, chalcocite, covellite and molybdenite. Luzonite and tennantite are abundant, especially in the brecciated ores. Pyrite is abundant peripherally. In addition, there are smaller quantities of sphalerite, galena, and a few rarer minerals.

The typical massive sulphide ore represents a more or less complete replacement of rock and gangue minerals and characteristically consists of irregularly oriented blebs of chalcopyrite in bornite, the latter, especially above the eleventh level, much replaced by chalcocite and covellite. In addition to the massive aggregates, there are veins and scattered patches of sulphides.

Molybdenite is rather abundant and occurs well distributed throughout the ore body. It is commonly disseminated in small grains throughout masses of kaolin and mica, although, in places, it forms in larger foliated bunches with chalcopyrite. Wherever molybdenite occurs with another sulphide, the associated sulphide is invariably chalcopyrite. The same may be said of bornite, which never occurs alone but is always associated with chalcopyrite. A similar association is that of chalcocite and covellite,

except that although covellite is commonly unaccompanied by chalcocite, the latter is rarely found without some covellite.

In a quantitative study of the flotation products from the Colorada mill, A. M. Gaudin [2] found that chalcopyrite was the most abundant copper mineral, followed in order by covellite, gray copper, chalcocite, and bornite. From the polished sections, bornite appears to be second to chalcopyrite in abundance. This is probably due to its concentration in the massive sulphide bodies, whereas the gray-copper minerals, together with chalcocite, are more widely scattered throughout the ore body, especially in the brecciated ore.

MINERALOGY AND PARAGENESIS.

Sequence and Zoning. The bulk of the Colorada ore body was deposited under hypogene conditions. The sequence of events and mineralization was as follows:

Hypogene: *Hypothermal*

1. Pyrite.
2. Phlogopite mica, feldspar, quartz.
3. Molybdenite, chalcopyrite, bornite.
4. Chalcocite.
5. Covellite.

Mesothermal

Beginning of core alteration and brecciation.

6. Pyrite, galena, sphalerite, luzonite, tennantite, covellite, chalcopyrite.
7. Alteration intergrowths and reaction borders, involving chalcopyrite, covellite, chalcocite, and bornite.
8. Alunite.

Completion of core brecciation.

Supergene:

1. "Sooty" chalcocite.

Pyrite is disseminated through the Henrietta formation and the intrusive quartz porphyry near the ore body. Outside the ring dike there is first a zone characterized by stringers of chalcopyrite and glassy quartz veinlets anastomosing through soft, buff-colored, kaolinized rock. This zone passes outward into a zone

[2] Gaudin, A. M.: Unusual Minerals, Eng. & Min. Jour., vol. 134, p. 523, 1933.

in which the rock contains disseminated pyrite alone. Another irregular zone of pyritic mineralization is at the apex of the ore body, ranging from a few feet below to about fifty feet above the fifth level.

The copper sulphides of the ore body also exhibit a noticeable zonal arrangement. Thus, although chalcopyrite and bornite occur intergrown in about equal amounts in the lower levels of the mine, the former increases and the latter decreases above the eighth level. Blue chalcocite and covellite are most prominent on the eighth, ninth and tenth levels; only minor quantities occur in the bornite below the tenth level; they also decrease upward along with the bornite. This zonal arrangement involves a locus of copper deposition between the ninth and tenth levels. At this center the copper is in greatest excess over sulphur and iron. Outward in every direction from this locus there is a relative increase in sulphur and iron, until in the altered rock outside the ore body iron and sulphur only are present in the form of pyrite.

Molybdenite, Chalcopyrite, and Bornite Mineralization.—The first stage in the deposition of the Colorada ores was the hypogene mineralization in which molybdenite, chalcopyrite, and bornite played the principal rôle. There is little to indicate any sequence between these minerals. The contacts between chalcopyrite and bornite are of the mutual-boundary type which may or may not indicate simultaneous deposition.[3] The fact that chalcopyrite exists as irregular, isolated blebs that are oriented within the surrounding bornite may point to a succession of the two.[4]

The intergrowths of chalcopyrite and bornite of this stage exhibit the largest of the sulphide textures. The textures of the succeeding replacements are characterized by decreases in grain size. Thus, the chalcopyrite and bornite intergrowth formed the foundation upon which the later sulphide replacements have largely been built. It is now preserved perfectly only in the ore of the eleventh, twelfth, and thirteenth levels.

Rarely the bornite contains small, irregular, embayed grains

[3] Bastin, E. S., *et al.*: Criteria of Age Relations of Minerals. ECON. GEOL., vol. 26, p. 605, 1931.

[4] *Idem*, p. 599.

of a light salmon-pink mineral which could not be definitely determined. It is always confined to bornite or may be residual in chalcocite or covellite after the replacement of the surrounding bornite. Etch tests and physical properties suggest the very rare mineral germanite (Cu_xGeS_y).

Hypogene Chalcocite.—It has been shown by Posnjak, Allen, and Merwin [5] that chalcocite formed above 91° C. is isometric and will remain in that state upon cooling provided it contains 8 per cent. or more of covellite in solid solution. If the amount of covellite is less than this, inversion to the orthorhombic form takes place at about 91° C. Some authors believe that the octahedral partings may be retained even after inversion; others are of the opinion that similar directions of parting result from the replacement of bornite, which has a similar octahedral cleavage. It has been generally considered that chalcocite assumes bluish tints when covellite is present in solid solution, although Schneiderhöhn and Ramdohr [6] state that the cause of the color is not quite clear. If chalcocite is proved to be isometric, then it is of hypogene origin and, in addition, must contain at least 8 per cent. covellite. It is also obvious that some hypogene chalcocite may become orthorhombic through inversion, and furthermore, as pointed out by Lindgren,[7] hypogene chalcocite may have formed below 91° C. and therefore never have been isometric. Supergene chalcocite is invariably orthorhombic.

There are certain criteria which can be used as reliable evidence of hypogene origin of chalcocite. The possession of isometric symmetry is perhaps the most reliable of these. The following evidence has been used by various authors to demonstrate the isometric character of chalcocite:

1. Complete isotropism with polarized light under crossed nicols.

2. Distinct steel blue color, thought to indicate the presence of enough dissolved covellite to prevent inversion on cooling below 91° C. to the orthorhombic form.

[5] The Sulphides of Copper. ECON. GEOL., vol. 10, p. 526, 1915.

[6] Schneiderhöhn, H., and Ramdohr, P.: Lehrbuch der Erzmikroskopie, Bd. 2, p. 289. Gebrüder Borntraeger, Berlin, 1931.

[7] Lindgren, W.: Mineral Deposits, p. 945. McGraw-Hill, New York, 1928.

3. Etching, replacement, or ex-solution along isometric structures, producing triangular and rhombic outlines.

4. X-ray pattern.

Of these evidences of isometric chalcocite, that of the X-ray pattern is the best. Complete isotropism is good evidence, but very weak anisotropism of orthorhombic supergene chalcocite may be easily overlooked. On the other hand, it is well to remember that isometric chalcocite is often anisotropic. The blue color of chalcocite is good evidence of hypogene origin but must be used cautiously, as the apparent color varies with the associated minerals. Absence of blue does not rule out isometric chalcocite. Isometric structure as revealed by etching, replacement or ex-solution is reliable evidence, especially if the patterns developed are coarse. However, it is possible that such patterns may have been inherited by supergene chalcocite in replacing such isometric minerals as chalcopyrite or bornite, although true ex-solution textures would not exist in this case.

As already pointed out, hypogene chalcocite with less than 8 per cent. dissolved covellite will invert to the orthorhombic form on cooling below 91° C. If this has happened, the problem then resolves into demonstration of the isometric ancestry of the chalcocite. This is often difficult, but the following indications have been used:

1. Large grain size, as revealed by etching, serving as confirmatory evidence.

2. Replacement of the coarse-grained chalcocite by finer-grained chalcocite which can be shown from other evidences to be definitely of supergene origin.

3. Close association or interlocking with grains of the same size which have failed to invert to the orthorhombic form because of more than 8 per cent. covellite dissolved locally.

4. Rose-gray color of chalcocite, supposedly due to solid solution of bornite in chalcocite formed above 91° C. (Bornite may be closely associated in small amounts as the product of unmixing.)

5. Lamellar rhombic chalcocite, which, according to Schneider-

höhn and Ramdohr,[8] is a paramorph after normal chalcocite formed above 91° C.

Hypogene orthorhombic chalcocite may also form below 91° C., in which case it should more nearly resemble supergene chalcocite,

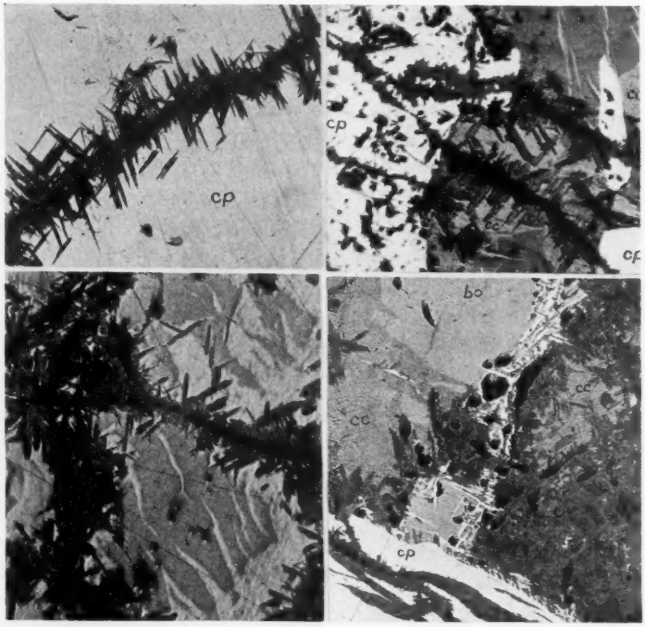

FIG. 1. Covellite veinlet formed along a fracture in chalcopyrite. × 130.

FIG. 2. Chalcocite and covellite developed largely at expense of bornite. Note that covellite is confined to chalcocite, and restricted upon entering chalcopyrite. × 80.

FIG. 3. Chalcocite replacing bornite and in turn replaced by covellite. Same section as Figs. 7 and 8. The textures of the three are intimately associated. × 60.

FIG. 4. Bornite replaced by chalcocite, which is in turn replaced by covellite. Note reaction rims of chalcopyrite and covellite. × 62.

cv, covellite; *cp*, chalcopyrite; *cc*, chalcocite; *bo*, bornite.

[8] *Op. cit.*, p. 295.

but criteria 1 and 2 may here be applied. Since in this case isometric ancestry never existed, more general evidence, other than symmetry and applicable to any mineral, must be used, such as:

1. Position definitely below a distinct zone of supergene enrichment.

2. A definite counterpart in some sort of hydrothermal zonal arrangement of elements and minerals.

3. Replacement of the chalcocite by minerals containing elements not present in earlier minerals, or replacement by minerals which can be definitely shown to be of hypogene origin.

In summary, the best indications of hypogene chalcocite are: (1) Proof of isometric form, for which the x-ray evidence is the most decisive; (2) proof of isometric ancestry, which may or may not need the support of more general evidence; and (3) replacement of the chalcocite by minerals definitely shown to be of hypogene origin.

In the Colorada ore body there are two types of chalcocite, one a gray-white variety which occurs only in minor quantities in the upper levels of the mine, the other a blue variety which occurs distributed throughout most of the ore body. The blue variety is isometric and hypogene in origin. It displays faint anisotropism which becomes more distinct when etched. The decisive proof of the isometric character of the blue chalcocite was furnished by Dr. Linus Pauling, of the California Institute of Technology, who made powder photographs of a sample of covellite and of a sample of chalcocite including some covellite. The intimate association of covellite with chalcocite made it impossible to get chalcocite powder without some covellite. Dr. Pauling very kindly contributed the following statement:

> Powder photographs of a sample of covellite and a sample of covellite plus chalcocite, provided by Mr. Kelley, were prepared, using a cylindrical camera 6.38 cm. in radius, and molybdenum K-radiation filtered through zirconia. The covellite photograph showed about twenty-six lines, the pattern being similar to that reported by Kerr.[9] The other photograph showed all but two or three of the covellite lines, and in addition a line of medium intensity at $d = 1.97 \pm 0.01$ Å. This might be either that re-

[9] Bateman, A. M., and Lasky, S. G.: Covellite-Chalcocite Solid Solution and Ex-solution. ECON. GEOL., vol. 27, p. 70, 1932.

ported by Kerr at 1.975 Å for isometric chalcocite, or that at 1.96Å for orthorhombic chalcocite. However, there was no trace of a line at 2.42 Å, reported as very, very strong by Kerr for orthorhombic chalcocite, although a line of one-tenth the intensity of that at 1.97 Å (also reported as very, very strong) would have been observed. Isometric chalcocite would show no other strong lines, according to Kerr.

Hence I conclude that the chalcocite in the sample is the isometric form, the orthorhombic form, if present at all, comprising less than 10 per cent. of the total.

The x-ray evidence of isometric chalcocite is confirmed by examination of the polished surfaces. The uniform steel-blue color of this chalcocite probably indicates the presence of more than 8 per cent. of covellite in solid solution in the chalcocite, which prevented the transformation of the hypogene chalcocite to the orthorhombic form on cooling below 91° C. The chalcocite also contains an abundance of triangular and rhombic patterns resulting from the later deposition of covellite. These patterns, together with etch patterns, are amply illustrated by the accompanying figures.

Up to the time of the deposition of the blue chalcocite and associated covellite the only metals introduced into the ore deposit were molybdenum, copper, and iron. Thus, the replacement of the early copper sulphides, including chalcocite and covellite, by such minerals as luzonite, tennantite, galena, and sphalerite represents a new hydrothermal mineralization. Luzonite and tennantite are most generally considered primary minerals. They are included by Lindgren [10] as following chalcopyrite and bornite in the usual sequence of mesothermal ores. Recently Bastin,[11] in a discussion of types of copper deposits, states that "the presence in the Kennecott ores of minor amounts of such minerals as enargite, tennantite, and luzonite indicates moderately high temperatures of mineralization and probably implies an igneous source." Schwartz [12] also lists as reliable evidence of hypogene

[10] Lindgren, W.: *Op. cit.*, p. 614.

[11] Bastin, E. S.: Criteria of Age Relations of Minerals. Econ. Geol., vol. 28, p. 438, 1933.

[12] Schwartz, G. M.: Microscopic Criteria of Hypogene and Supergene Origin of Ore Minerals. Econ. Geol., vol. 27, p. 543, 1932.

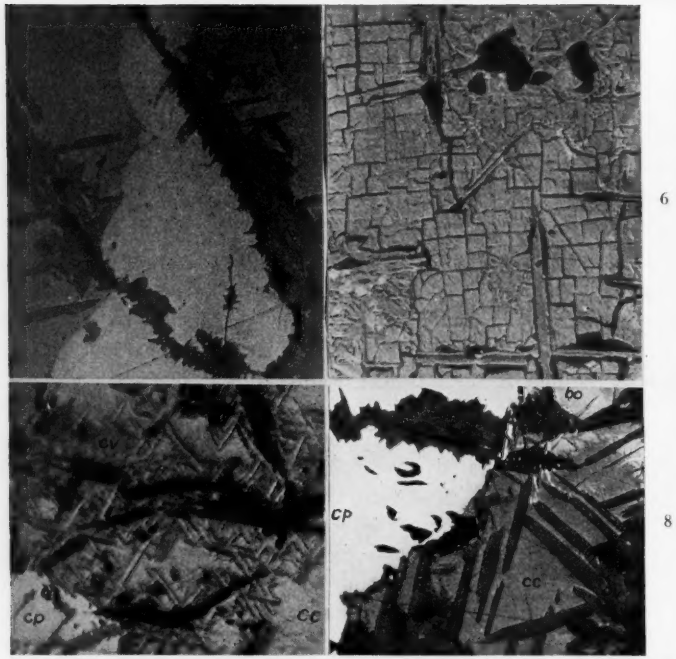

FIG. 5. Fracture veinlets of covellite in chalcocite and chalcopyrite. Note change in texture of covellite veins on entering chalcopyrite. × 70.

FIG. 6. Chalcocite replacing bornite and in turn replaced by covellite. (Etched with HNO_3.) Same section as Figs. 7 and 8. The textures shown in the three photographs are intimately associated. × 65.

FIG. 7. Rhombic and triangular patterns of covellite developed in chalcocite. Note restriction of covellite in chalcopyrite. × 70.

FIG. 8. Laths of covellite oriented along octahedral partings in chalcocite, a micro-texture commonly considered as indicating unmixing. Note texture of covellite in chalcopyrite and secondary chalcopyrite along and within covellite laths. Also note splitting in some of the covellite crystals, with unreplaced chalcocite down the centers. × 170.

mineralization the introduction of new elements not included among the earlier minerals.

The existence of the gray-white " sooty " chalcocite in the upper levels of the mine lends support to the evidence pointing towards a primary origin for the blue chalcocite. The etching of the " sooty " chalcocite is decidedly fine and, in contrast with the blue chalcocite, shows no regular pattern. The " sooty " chalcocite replaces alunite, which is one of the latest of the hypogene minerals to replace blue chalcocite.

In view of such an array of evidence for hypogene chalcocite, added to Dr. Pauling's conclusions, it is safe to conclude that all the blue chalcocite is of hypogene origin.

One of the most outstanding features of the chalcocite deposition in the Colorada deposit is the selective replacement of bornite in chalcopyrite-bornite mixtures (Fig. 2). Chalcocite veins that cut bornite end abruptly at chalcopyrite masses, or where such veins continue into the latter mineral they change to covellite.

Schwartz [13] has listed criteria for distinguishing the supergene or hypogene origin of ore minerals. Among the reliable criteria for supergene origin is listed selective replacement of bornite by chalcocite or covellite. In support of this Schwartz refers to the work of Graton and McLaughlin [14] at Engels, California. They conclude that one evidence favoring a supergene origin for chalcocite was the greater susceptibility to replacement shown by bornite as compared with chalcopyrite, and state that such a phenomenon " is entirely in accord with repeated observations in examples of unquestioned downward enrichment and with results of experiments in artificial enrichment." The same authors also point out that " in the conversion of bornite to chalcocite, only a relatively small addition of copper is required to produce a result of important magnitude, for the one mineral (bornite) contains 63.33 per cent. copper or almost four-fifths as much as the other, viz. 79.86 per cent." For the conversion of chalcopyrite to chalcocite almost 2.5 times as much copper originally present must be added.

[13] *Idem*, p. 552.

[14] Graton, L. C., and McLaughlin, D. H.: Ore Deposits at Engels, California. Econ. Geol., vol. 12, p. 30, 1917.

Turner and Rogers,[15] who had previously studied the ores from the Engels mine, concluded that the chalcocite and covellite are of hypogene origin, and also pointed out the pronounced development of these minerals at the expense of bornite.

Tolman and Clark,[16] in experiments with copper in solutions, found that dispersed copper sulphides upon coagulating in the presence of bornite and chalcopyrite had a much greater tendency to accrete to the former.

The point which it is intended to make here is that selective replacement of bornite is not sufficient evidence in itself to indicate the supergene origin of chalcocite. That such selection existed under hypogene conditions is substantiated by the instances at the Colorada mine and perhaps also at Engels. It is as expectable and natural in hypogene replacement as in supergene replacement, and the high copper content of bornite as compared to chalcopyrite has an important influence under hypothermal conditions.

Texture of the Covellite.—Covellite is closely associated with the blue chalcocite but appears from the textural relations to be clearly later than the chalcocite. As stated earlier, blue chalcocite without covellite is rarely observed. On the other hand, covellite commonly occurs in chalcopyrite without chalcocite, but it is always more prominent in chalcocite. (Figs. 2, 8.)

The covellite crystals range in size from the minute crystals in fine intergrowths to laths nearly one half millimeter in length. The average dimensions of the lath-shaped crystals seen on the polished surface are about 0.02 × 0.2 mm.

The covellite crystals may be isolated and scattered irregularly through the chalcocite or, on the other hand, they may be so numerous as to form a covellite mesh or felted mass. Orientation of the covellite into triangular and rhombic patterns following the chalcocite structure is a prominent feature, as is shown in the accompanying photomicrographs. The crystallographic control

[15] Turner, H. W., and Rogers, A. F.: A Magmatic Sulphide Deposit. ECON. GEOL., vol. 9, p. 383, 1914.

[16] Tolman, C. F., and Clark, J. D.: Copper in Electrolytic Solutions. ECON. GEOL., vol. 9, p. 577, 1914.

of the chalcocite over the covellite patterns commonly shows a persistent parallelism over areas of two or three millimeters.

Covellite also develops in irregular veinlets, which appear clearly to be related to small irregular fractures developed in the chalcocite and chalcopyrite (Fig. 1). The contraction of these veinlets from large, jagged veinlets in chalcocite to small feathery veinlets on entering chalcopyrite is an especially characteristic feature of the covellite replacement. In addition to the prominent development of covellite at the expense of chalcocite, covellite forms peculiar alteration intergrowths with chalcopyrite and chalcocite in bornite (Fig. 9). Closely allied with these intergrowths is the development of covellite with the same assemblage to form reaction "rims" along earlier mineral contacts (Figs. 4, 12).

Recently Bateman and Lasky[17] showed experimentally that covellite can be made to go into solid solution with chalcocite upon heating. To a certain extent textures produced by their experiments duplicated the intergrowths described from the Kennecott ores. A similar unmixing they believed occurred naturally in the Kennecott ores.

Bateman[18] found by heating specimens of chalcocite and covellite in an attempt to drive covellite into solid solution, that where the quantity of covellite reached or exceeded 30 to 40 per cent. of the chalcocite present, solid solution was not complete. Frayed remnants of covellite remained undissolved. He also found that where covellite formed 90 to 95 per cent. of the chalcocite and covellite present, only the covellite immediately surrounding the chalcocite disappeared, and the remainder of the covellite was unaffected. From Bateman's experiments it seems reasonable to suppose that there is a limit to the amount of covellite that can be held in solid solution by chalcocite, and conversely that there is a limit to the amount of covellite that can be derived from chalcocite by unmixing. Although Bateman believes that chalcocite can hold as much as 30 per cent. covellite, it should be noted that Schneiderhöhn and Ramdohr[19] are considerably more conser-

[17] *Op. cit.*, p. 84.

[18] Bateman, A. M.: Some Covellite-Chalcocite Relationships. ECON. GEOL., vol. 24, p. 438, 1929.

[19] *Op. cit.*, p. 281.

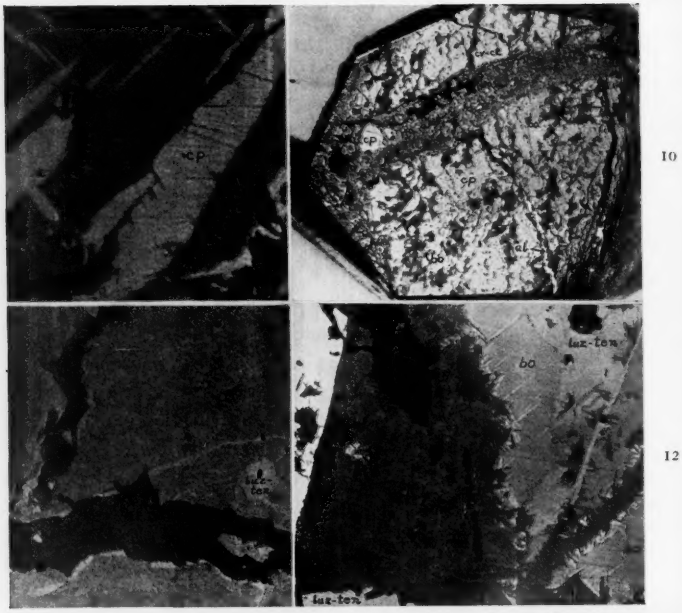

FIG. 9. Chalcopyrite and covellite replacement, largely governed by the structure of the bornite. The intergrowth probably represents an alteration due to the break-down of the bornite. × 960.

FIG. 10. Polished section showing transection of earlier copper sulphides by a luzonite-tennantite vein. The brecciated appearance of the vein is due to the intimate mixture of alunite with luzonite and tennantite. Note cavities in vein and alunite filling of a fracture in the sulphides at the lower right. × 2.

FIG. 11. Tennantite and alunite veins cutting covellite and chalcocite. Note close association of the two vein minerals, also the light color of the tennantite as contrasted to the patch of blue chalcocite (center). × 140.

FIG. 12. Bornite replaced by chalcocite, covellite, chalcopyrite, and luzonite. Some covellite appears to be contemporaneous with luzonite although just outside the field a luzonite-tennantite vein cuts the entire specimen. Note that the chalcocite in the center shows only slight contrast to the bornite areas on either side. × 140.

al, alunite; *luz-ten*, luzonite-tennantite.

vative on this point and contend that 16 per cent. is the maximum. The statement is made in Dana's Textbook of Mineralogy [20] that chalcocite can hold "as much as 8 per cent. CuS" in solid solution. Covellite in excess of these percentages should not be interpreted as having been derived from chalcocite by unmixing. It is therefore impossible to assign an unmixing origin for covellite unless enough chalcocite is present.

Since among the Colorada sulphides covellite exceeds chalcocite, the covellite can not be due to unmixing. Furthermore, since it is veined by such minerals as luzonite and tennantite, which are hypogene, it could not be supergene unless the two belong to separate epochs of mineralization, of which there is no evidence. That the covellite is not the product of unmixing is further supported by the presence of the blue isometric chalcocite which is now believed to hold at least 8 per cent. covellite in solid solution. Since at least this proportion of covellite may be present in solid solution in the chalcocite, not over 22 per cent., or less than one quarter, of the covellite crystals could have resulted by unmixing from the chalcocite even if Bateman's figure of 30 per cent. for the maximum solubility of covellite in chalcocite is accepted. But this figure is probably too high. Bateman and Lasky [21] themselves point out that the disappearance of covellite on polished surfaces of chalcocite and covellite was only a surface phenomenon, for on repolishing the specimen the vanished covellite was found again "under a relatively thin layer." Reheating only dissolved a fraction of the covellite, and when the specimen was repolished and heated a third time no covellite could be made to disappear. This probably indicates that the chalcocite of the specimen was saturated with covellite. If this is true the proportion of covellite which the chalcocite could hold should have been figured from the volume of chalcocite in the specimen rather than the area of chalcocite on the polished surface.

The conclusion drawn by Bateman and Lasky [22] that the felted

[20] Ford, W. E.: Dana's Textbook of Mineralogy, 4th ed., p. 420. John Wiley & Sons, New York, 1932.

[21] *Op. cit.*, p. 73.

[22] *Idem*, p. 85.

masses of their diabasic covellite represent the final step in unmixing of covellite from chalcocite, seems to require too much of the chalcocite; the isolated laths of covellite shown in their Figure 1 [23] might have formed by replacement.

In regard to artificially formed covellite, Bateman and Lasky state: [24]

> The unmixed crystals of covellite do not cross each other, they continue their growth until another crystal is encountered, when one of them stops and the other continues. Commonly, crystals taper at their junctions. This description resembles that of the natural intergrowths previously described, and bears out Per Geijer's contention that such a structure is characteristic of unmixing and may be used to distinguish unmixing from replacement.

In the Colorada ores enlarged junctions and tapering junctions between covellite crystals are commonly found together in which the covellite has apparently been deposited by transfer of material (Fig. 7). From this arises the question, does tapering at the junctions always indicate unmixing, or may it also be a characteristic feature of metasomatic covellite? Tapering of covellite plates at their edges is the normal result of their growth. The replacement criterion of enlarged junctions refers to veins made up of many small crystals. Single crystals or blades are apt to terminate upon encountering one another. When a covellite crystal terminates, it tapers whether formed by replacement or any other method.

In view of the conclusions drawn by Bateman and Lasky as a result of their experiments with chalcocite and covellite, the possibility that some unmixing took place is recognized. For example, chalcocite may be deposited accompanied or followed by hypogene covellite. The chalcocite very possibly may have considerable covellite in solid solution, and with lowering of temperature below 91° C. covellite plates may develop (in limited quantities) by unmixing along the host structure. But the metasomatic covellite may have previously developed (above 91° C.) in accordance with the same structure. The unmixing covellite might

[23] *Idem*, p. 57.
[24] *Idem*, p. 81.

either increase the size of the metasomatic covellite or form new covellite. The texture of covellite formed in either way might be the same, and therefore it is not clear how a distinction can be made between metasomatic and ex-solution covellite. The ex-solution covellite is limited as to quantity. The metasomatic covellite is not limited in its development and may spread to form extensive masses or large irregular veins. On the other hand, metasomatic covellite alone may develop, restricted to small isolated crystals or blades outlining the symmetry of the host mineral, and thus be identical with that formed by unmixing.

Schwartz,[25] in his recent article on unmixing textures, states: "Any positive criterion of replacement is a negative criterion of ex-solution." In view of the abundance of covellite and the jagged, irregular replacement veins which are so closely associated with rhombic and triangular covellite patterns, it is reasonable to conclude that the Colorada covellite of this stage originated by metasomatic replacement along with or closely following the chalcocite.

Luzonite-Tennantite Intergrowths.—Veins of luzonite and tennantite up to nearly an inch in width cut sharply across aggregates of the earlier sulphides. The luzonite and tennantite of the veins are intimately and thoroughly intermixed. The luzonite is faintly pink and light enough so that it is often difficult to distinguish it at once from the associated tennantite. The tennantite is very light gray and appears light in contact with blue chalcocite. It is distinctly isotropic, whereas luzonite is strongly anisotropic.

Some tetrahedrite, famatinite, or freibergite may be present with luzonite and tennantite, but from etch tests, optical properties, and blow-pipe tests, the bulk of the sulpho-salts appears to belong to the arsenic group, luzonite and tennantite.

Covellite is especially common, disseminated through the sulpho-salts, and occasionally small rounded patches of residual bornite and chalcopyrite are seen. Patches of sphalerite may be associated with the minerals of this stage. Patches and veins of

[25] Schwartz, G. M.: Textures Due to Unmixing of Solid Solutions. ECON. GEOL., vol. 26, p. 762, 1931.

luzonite and tennantite may contain alunite in such quantities as to be largely replaced by the late gangue mineral.

In addition to occurring as veins in the earlier sulphides, the sulpho-salts occur as coronas around fragments of sulphides surrounded by alunite.

An interesting bit of late primary mineralization in the form of several veins one to two inches in width cuts the entire ore body between the twelfth and thirteenth levels. The veins are composed of galena, sphalerite, tennantite, chalcopyrite, covellite and alunite, with an apparent sequence in the order given. These minerals are included with the luzonite-tennantite deposition as being probably of the same age because of the common presence of tennantite and sphalerite, although luzonite was not noted in the extensive veins of the bottom levels. Sphalerite occurs in a few places as a filling in a chalcopyrite breccia.

The covellite grains and veinlets present in the luzonite and tennantite are not mere replacement remnants of the earlier covellite, but represent another primary deposition which was contemporaneous with the sulpho-salts. This covellite is characterized by its fine mesh-like texture and in some instances exhibits wavy banding with chalcopyrite, suggestive of colloidal origin. Some of this covellite forms small veinlets cutting the luzonite and tennantite, indicating that some of the covellite at least was later than the sulpho-salts. The contacts of these veinlets are regular in contrast to the jagged needle-like veins of the earlier covellite.

"Reaction" Rim Minerals.—There is an abundance of chalcopyrite, chalcocite, covellite, and a little bornite, developed along and near mineral boundaries. The crystals and textures involved are distinctly smaller than the intergrowths upon which they are built. Such intergrowths are commonly called reaction rims, and their development in the Colorada ore body is a hypogene phenomenon. At bornite-chalcopyrite contacts the rims are generally confined within the bornite and in many cases spread through the bornite. Such replacements are commonly, but by no means everywhere, formed along the isometric structure of the bornite.

In detail, such intergrowths may be composed of lenticular aggregates of chalcopyrite and covellite (Fig. 9). Similar intergrowths of chalcopyrite and chalcocite are also common.

If, in a primary intergrowth of chalcopyrite and bornite, conditions are set up in which chalcopyrite begins to replace adjoining bornite areas, copper in excess of that needed to form the invading chalcopyrite becomes available, and covellite or chalcocite may form. Many textures such as those shown in Figure 9 are believed to have formed in this fashion. Such intergrowths appear to be somewhat more common where the chalcopyrite is greatly in excess of the bornite.

A little bornite was noticed in a reaction rim between early chalcopyrite and a vein of luzonite and tennantite. Bornite formed on the chalcopyrite side and covellite formed on the vein side. Between the two, chalcopyrite and covellite formed a still finer-grained secondary reaction rim.

The development of the reactionary intergrowths was in all probability not confined to one time period as indicated in the tabulated sequence of mineralization, but formed at all stages in the sequence of replacing sulphides. It was inserted in the sequence after the sulpho-salt deposition only because so much of it forms along the luzonite-tennantite veins and because they were the latest reaction rims observed.

Alunite and Core Brecciation.—Alunite is distinctly the latest of the hypogene minerals. In the majority of cases it clearly replaces all the sulphides with the exception of the supergene "sooty" chalcocite. It is distributed throughout the mine in gangue and sulphide alike.

In many instances alunite appears closely associated with luzonite and tennantite. In alunite breccias of the earlier sulphides, luzonite-tennantite intergrowths commonly form as coronas around the fragments. Rarely the alunite cuts through the coronas, but the coronas are too even and continuous to have been remnants of an earlier replacement. Discontinuous veinlets of the sulpho-salts are commonly developed along the borders of alunite veins (Fig. 11).

Although alunite cuts many luzonite-tennantite veins, in general the textures are such as to indicate that at least part of the sulpho-salt deposition was contemporaneous with the alunite. There is much to suggest that the alunite and sulpho-salts of copper were carried, in part at least, by the same solutions, and, on replacing earlier minerals, the sulpho-salts tended to accrete to the sulphide fragments and thus gave rise to the coronas. The complete precipitation of the alunite followed later, and in some instances the coronas were cut by the late alunite. It appears also that the earlier sulphides were often dissolved by these late sulphate solutions, resulting in cavities filled later by luzonite-tennantite intergrowths and covellite in crustified bands. Some of the cavities were entirely filled with sulphide, some left open, and some filled later with alunite.

At the Colorada ore body alunite occurs distributed from the top to the bottom of the mine. If oxidized descending solutions had formed the alunite to this depth, oxidized copper minerals and secondary sulphides would have been prominent. Oxidized copper minerals and secondary sulphides are rare and occur only in minor quantities above the main primary sulphide ore body. Ford,[26] in summing up the occurrence of alunite, indicates that its formation is due "to the presence of sulphuric acid solutions or vapors," and that "the conditions of formation usually indicate high pressures and temperatures." Thus, because of its distribution and close association with the primary minerals luzonite and tennantite, the conclusion is reached that the alunite at the Colorada mine is hypogene in origin and probably formed from acid solutions.

The acid solutions which brought in the luzonite-tennantite mineralization gradually altered the entire ore-body core and converted it into an incompetent mass upon which brecciation proceeded. However, the brecciation began early, before alteration was complete, and the two progressed and followed each other as cause and effect. But before alteration and brecciation had progressed far, the new sulphides and sulpho-salts began to be deposited as veins and as coronas around the early sulphide frag-

[26] Ford, W. E.: *Op. cit.*, p. 768.

ments. As brecciation proceeded, the luzonite-tennantite intergrowths were in turn brecciated, and then finally cemented with alunite derived from the rapidly altering rock. With complete alteration, brecciation was widespread until the entire core was a squeezed and brecciated mass which in many places involved much of the ore and pegmatite rings. Alunite was also caught up in the final and complete brecciation.

"Sooty" Chalcocite.—"Sooty" gray chalcocite is not prominent at the Colorada mine. The best explanation for this is that the top of the main body of copper sulphides lies some seven or eight hundred feet below the surface, and although solutions admittedly may have penetrated deeper than this, the circulation was probably poorer at such depths and the amount of copper available above this depth was small. C. H. White,[27] in an article on supergene enrichment at Cananea, cites evidence that the water table has been considerably nearer the surface than it is at present. This, White thought, was substantiated physiographically by the recent trenching of the broad alluvial fans that have been built up on the old mesa erosion surface to the east of the Cananea Range. Since the water table has until recently stood much higher than it is at present, long continued oxidation and downward circulation to great depth has been prevented.

The secondary chalcocite examined in polished sections is in the form of "sooty" coatings and very thin seams in fractured and brecciated pyrite. Much of this pyrite was earlier replaced by alunite, in which instances the gray chalcocite has impregnated the alunite and formed replacement coronas around the pyrite fragments. One small pyrite vein was noted in the upper part of the mine which had been partly replaced by a smaller vein of luzonite. The luzonite in turn was replaced by gray chalcocite.

CONCLUSIONS.

All the sulphides of the Colorada ore body with the exception of a little "sooty" chalcocite were deposited under hypogene conditions. Proof that the blue chalcocite of the Colorada ore body

[27] White, C. H.: Supergene Enrichment of Copper Below a Lean Pyritic Zone. ECON. GEOL., vol. 19, p. 726, 1924.

is isometric and hence hypogene is furnished principally by x-ray results. Additional evidence that both chalcocite and covellite are hypogene is furnished by the replacement of these minerals by such hypogene minerals as luzonite and tennantite.

As at Kennecott, chalcopyrite and bornite form the early foundation upon which the succeeding intergrowths were built, but, unlike the Alaskan occurrence, the hypogene chalcocite deposition was interrupted before it had developed to the prominence attained at Kennecott. Bateman and Lasky have offered ex-solution as one means by which the covellite transition textures were derived from the chalcocite in the Kennecott ores. Similar textures, including triangular outlines and diabasic intergrowths, are strikingly developed in the Colorada ores, but it is believed that the evidence points towards an origin by replacement rather than by unmixing. If any unmixing took place it probably played only a subordinate rôle.

There does not appear to be anything characteristic about the artificial unmixing textures produced by Bateman and Lasky which could not be duplicated in nature by replacement. Tapering of covellite crystals at junctions is no criterion of unmixing. The replacement criterion of enlarged junctions applies to veins and not to individual blades or crystals. Covellite plates normally taper at the edges.

Covellite derived from chalcocite by natural unmixing is confined to thin blades formed along parting planes in chalcocite. However, similar blades may be formed by replacement, and it is therefore not clear how the ex-solution texture could be identified. The figure of 16 per cent. given by Schneiderhöhn and Ramdohr as the quantity of covellite which chalcocite can hold in solid solution appears to be more nearly correct than the larger figure of 30 per cent. given by Bateman, especially in view of the later results of Bateman and Lasky after repolishing and reheating treatment of the chalcocite and covellite.

When covellite is present in excess of, for example, 16 per cent., it is evidence of replacement origin of the covellite, and positive evidence of replacement is negative evidence of unmixing. Fur-

thermore, if the associated chalcocite present is blue and isometric as it is at the Colorada mine, as much as 8 per cent. should be deducted from the total to obtain the percentage used as the amount of covellite which could have unmixed from chalcocite. It is unsound to conclude an unmixing origin for covellite in excess of these percentages.

The selective replacement of bornite by chalcocite and covellite was demonstrable under hypogene conditions in the Colorada ores and therefore it cannot be used as a dependable criterion for supergene replacement, as has been advanced by Schwartz.

The close association of luzonite and tennantite with alunite is taken to indicate that all the ore minerals of this stage were deposited from acid solutions that were strictly hypogene in origin. Alunite is clearly the latest of the hypogene minerals and is only followed by minor amounts of supergene chalcocite.

Covellite develops textures varying from scattered plates to feathery and mesh-like aggregates. Feathery covellite is thought to indicate a supergene origin and has been listed as a reliable criterion of such origin.[28] In the Colorada ores continuous veins of covellite are characteristically bladed and lath-like in chalcocite and upon entering chalcopyrite develop in feathery veins and aggregates. The later covellite associated with luzonite and tennantite is invariably feathery. There is a very noticeable tendency towards diminution of size of texture in the replacements proceeding with decreasing temperatures and pressures. It is apparent that covellite texture depends upon the character of the host mineral as well as upon the character of the solutions and the temperature and pressure. The development of feathery covellite under hypogene conditions makes it apparent that this texture can not be used as an infallible criterion of supergene origin.

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[28] Schwartz, G. M.: Microscopic Criteria of Hypogene and Supergene Origin of Ore Minerals. ECON. GEOL., vol. 27, p. 548, 1932.

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BALCH GRADUATE, SCHOOL OF THE GEOLOGICAL SCIENCES,
CALIFORNIA INSTITUTE OF TECHNOLOGY,
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Oct. 5, 1934.

THE GEOLOGY OF CASTLE-AN-DINAS WOLFRAM MINE, CORNWALL.

E. H. DAVISON.

In the Geological Magazine for August, 1920, the writer gave a brief description of the geology of Castle-an-Dinas mine. Since then the mine has been much more developed and a clearer idea of its geology has been obtained. He therefore makes no apology for a second paper on the same area.

Castle-an-Dinas mine is situated on the northern slope of the hill of the same name which lies about two miles to the east of the town of St. Columb Major in Cornwall. It is about four miles

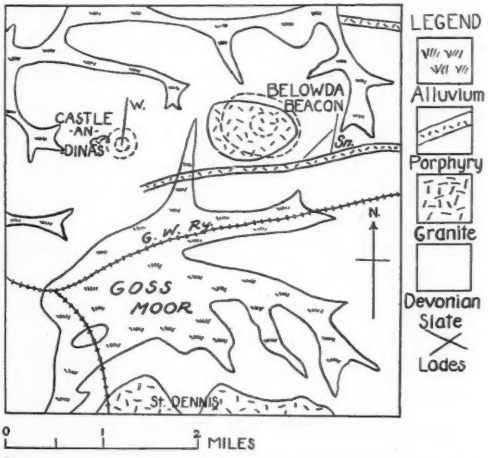

Fig. 1. Sketch map showing Castle-an-Dinas area.

to the north of the St. Austell or Hensbarrow granite mass (Fig. 1), and between it and the Hensbarrow hills lie the Goss Moors, where rich alluvial tin gravels were worked in the first half of

the last century. The hill is just over 700 feet high; the surrounding country lies between 350 and 400 feet above sea level. It is surmounted by a triple circular earth-work of early British age, which gives the hill its name, and is one of the reputed birth places of King Arthur. About one mile to the east of Castle-an-Dinas hill lies Belowda Beacon, a hill 740 feet high formed by a granite cupola; it contains veins of tin and wolfram, associated with greisen bands, and also an area of china clay.

In 1915 the outcrop of a lode was traced on the northern slope of Castle-an-Dinas hill, and this has been developed by means of adits.

THE ROCKS OF CASTLE-AN-DINAS HILL.

The bulk of the hill is composed of Devonian slates which belong to the Meadfoot series. They strike approximately east-west and are folded on axes parallel to their strike. The slates are red in color, with well developed cleavage; in some areas they show definite foliation. As the hill lies within the metamorphic aureole of the St. Austell granite mass, the slates show the effects of both dynamic and contact metamorphism. For the most part they are cleaved and foliated rocks, and the foliation consists of either alternating bands of quartz and tourmaline, or of quartz, and quartz with secondary mica. The slates are invaded by narrow veins of greisen and by veinlets of quartz with lithia mica and cassiterite (Fig. 3). These veinlets commonly show a "lit-par-lit" structure. Other minerals in the slates are wollastonite, andalusite, biotite and variscite, which in places lines the cleavage planes.

On the north side of the hill, near the summit, there is an outcrop of granite (Fig. 2). The rock has a fine-grained texture, with phenocrysts of orthoclase and quartz, both minerals being idiomorphic. It has, therefore, the texture of a granite porphyry, but underground exposures show it to be a normal coarsely crystalline granite. The character of the outcrop seems to be the result of the chilling of a small tongue of granite by the surrounding slate. This type of porphyritic granite has been

recorded at other localities, notably at St. Michaels Mount [1] and at St. Agnes Beacon.[2]

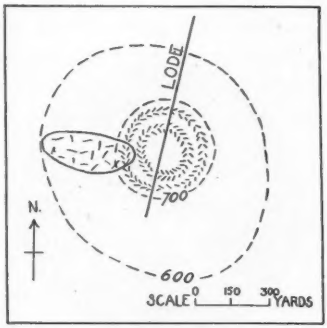

FIG. 2. Detail of Fig. 1, showing Castle-an-Dinas. (See legend, Fig. 1.)

The lode outcrops on the north side of the hill; it strikes N. 15° E., and has an average width of three feet. It occupies a vertical fissure in the slates; the filling consists essentially of white vein-quartz containing irregular patches of coarsely crystallized wolfram which vary in size from a few inches in diameter to several feet. The almost complete absence of other metallic minerals is remarkable; there are some stains of oxidized copper compounds, small plates of native copper, and small quantities of bismuth tungstate have also been found in a clay-filled veinlet that cuts the lode. The absence of cassiterite in the lode is shown by the fact that the wolfram concentrate obtained contains less than 0.25 per cent. tin oxide, in spite of the fact that no steps are taken to separate cassiterite from the wolfram. Cassiterite does occur, however, in the country rock; samples of slate from the walls of the lode have yielded 1.0 per cent. SnO_2.

The Castle-an-Dinas lode is almost unique in character when compared with the other wolfram lodes of Cornwall, which include the following types: (*a*) Pegmatite with wolfram and

[1] Davison, E. H.: Geology of St. Michaels Mount. Trans. Roy. Geol. Soc. Can., vol. 15, p. 34.

[2] Davison, E. H.: Handbook of Cornish Geology, p. 95.

cassiterite; (*b*) greisen veins with wolfram and cassiterite; (*c*) fissure lodes with wolfram, arsenopyrite, cassiterite and sometimes chalcopyrite.

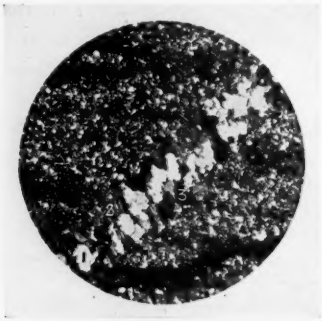

FIG. 3. Photomicrograph of altered slate from Castle-an-Dinas mine, St. Columb, showing granitic vein. (1) quartz; (2) gilbertite mica; (3) cassiterite (black).

The unusual features of the lode described above are:

I. The absence of minerals representing the volatile constituents of the granite magma, such as tourmaline, topaz, or fluorite. Tourmaline, although absent in the lode, is found in the country rock.
II. Almost complete absence of other metallic minerals.
III. The coarsely crystalline character of the vein filling.

MINING DEVELOPMENT AND UNDERGROUND GEOLOGY.

The mine consists of two levels, 60 feet apart, driven into the hill along the strike of the lode. Air shafts connect the upper level with the surface, and the two levels are connected by winzes and stopes (Fig. 4). The upper level has been driven nearly through the hill and the country rock is slate all the way, but there are bands of greisen and aplite in the slate near the center of the hill. The lower level starts in slate, but towards the center

of the hill the lode passes through granite for about 80 feet. This granite is completely kaolinized near the margin but is less altered in the center, where it is a medium-grained rock composed of quartz, orthoclase, albite, lithia mica and tourmaline. It was generally thought that this granite formed the crest of a granite cupola, but when a winze was sunk from the lower level it passed into slate again 10 feet below the level and continued in slate to a depth of 65 feet below the level. A rich lode was found the full depth of the winze and some feldspar occurs in the lode. The granite exposed in the level is therefore a tongue.

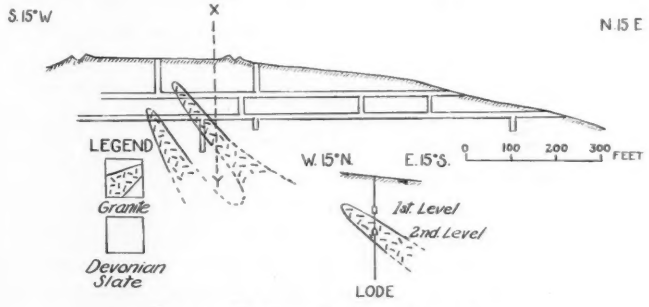

FIG. 4. Section, Castle-an-Dinas mine.

The latest development is the commencement of an adit, from the bottom of the valley to the north of the hill, at a depth of about 140 feet below the present lower level.

The ore is dressed chiefly by coarse crushing and then by jigs, the bulk of the wolfram concentrate having the size of fine gravel and a tungstic oxide content of 65 per cent. WO_3.

GENESIS OF THE LODE.

The sequence of events which culminated in the formation of the lode seems to have been:

I. Folding and cleaving of the slates.

II. Intrusion of the granite followed by the action of the volatile constituents of the granite, resulting in the deposi-

tion of cassiterite in the slate and the formation of greisen, kaolin and tourmalinized slate.

III. Opening of the lode fissure.

IV. Filling on the lode fissure by magmatic solutions, giving rise to a pegmatite which, near the surface of the granite, became a quartz wolfram lode.

SCHOOL OF MINES,
CAMBORNE, CORNWALL,
Nov. 7, 1934.

DISCUSSION AND COMMUNICATIONS

GOLD PLACER MINING ON SNAKE RIVER IN IDAHO.[1]

Sir: Gold in the gravel of the Snake River has been known since the early 1860's, when the first attempts were made to recover it by placer methods in western Wyoming, and a little later at several places in southern Idaho. Largely because of the extreme fineness of the gold particles, these early efforts were only moderately successful. Sporadic placer mining has continued, however, at many places along the river.

Many papers [2] deal with the placer methods and the probable source of the gold. The study by Day and Richards, which included the examination of about 200 samples of gravel from the Snake River in Idaho, is the most extensive that has been made. Several of their samples of black-sand concentrates from gravel near Minidoka contained, per ton of gravel, from 1 to 8 pounds of magnetite, 1 to 4 pounds of ilmenite, 1 to 4 pounds of garnet, and from 8 cents to $1.45 in gold.

Hill stated [3] that "practically all the gravels of Snake River Valley contain gold, but in most places the gold content is very small. The problem of saving the fine gold has not been entirely solved and perhaps may be in the direction of cyanide."

[1] Published by permission of the Director, U. S. Geological Survey.

[2] Day, D. T., and Richards, R. H.: Useful minerals in the Black Sands of the Pacific Slope. U. S. Geol. Survey, Min. Res., 1905, pp. 1175–1246, 1906; Schultz, A. R.: Gold Developments in Central Uinta County, Wyoming, and at Other Points on Snake River. U. S. Geol. Survey Bull. 315, pp. 71–88, 1907; Irvine, C. B.: Fine Gold of Snake River. Mining World, vol. 29, p. 916, 1908; Hill, J. M.: Notes on the Fine Gold of Snake River, Idaho. U. S. Geol. Survey Bull. 620, pp. 271–294, 1916; Hite, T. H.: Fine Gold and Platinum of Snake River, Idaho. ECON. GEOL., vol. 28, pp. 256–265, 1933; Special Features of Fine Gold from Snake River, Idaho: *Idem*, pp. 686–691; Fahrenwald, A. H.: Flotation of Gold from River Sand and Black Sand. Mining Journal (Phoenix, Ariz.), April 30, 1933, pp. 3–4.

[3] *Op. cit.*

Studies by Hite have shown that although some of the gold particles are so extremely small that several million would be required to equal the value of a cent, many of them are in the form of flakes that average about 3,000 to a cent (gold at $35 an ounce). Most of the gold ranges from 0.940 to 0.960 fine and is nearly free from other metals. Platinum has been recognized in some places, but the particles are nearly as fine as those of gold. Some platinum may be caught by amalgamation, but if so it is not reported separately by the buyers.

Fahrenwald's experiments on flotation were made on samples of sand and black-sand concentrates from the Snake River. He states that by flotation " no doubt 50-cent material under favorable conditions can be treated profitably if handled on a reasonable yardage basis."

All the gold is fine enough to be classed as " flour " gold, but probably only the finest particles, which constitute a small fraction of the total amount, float away during ordinary placer operations. With care, probably 90 per cent of the gold can be recovered. Attempts to work the gravel on a large scale with dredges have not been successful. Also cyanide and flotation methods have not been successful financially, chiefly because of the large investment required for equipment and the consequent high overhead charges. However, due to the increased price of gold, more properties have been operated during the last two years.

During the fall of 1934 the writers examined several properties under operation between King Hill and American Falls, along one of the most productive portions of the river.

About 6 miles below American Falls and three-quarters of a mile below " The Narrows," Mr. A. Alston was working bench gravel on bedrock about 30 feet above the river. The gravel there is partly cemented with carbonate but disintegrates readily under nozzle water. It carries more gold than does the gravel of lower slopes at this locality. Mr. Alston's equipment includes an unusual galvanized-iron trough with a false bottom of brass screen which has proved to be effective in rapidly separating the black sand and gold from the coarser and lighter materials.

Most of the black sand is caught on a blanket. The sand and gold are removed each day by rinsing the blanket in a tub. The sluice is lined with burlap, which collects the small amounts of black sand and gold that pass over the brass screen and the blanket. The burlap is removed and rinsed about once a week. The concentrates are put through a rocker, and the gold is caught on an amalgamated copper plate. Nearly $1,500 worth of amalgam was produced from May to October 1934, which represented wages of about $4 a day each for himself and a helper, after deducting $100 for materials and supplies and 75 cents a day for fuel.

On the upstream side of "The Narrows," Oscar Payne was working a deposit of bench gravel similar to the Alston property. A short distance farther upstream low bench gravel was being worked on the Kilgore property. About two miles farther upstream similar deposits of gravel on the north bank of the river were being worked on the Franklin property. Above this property Anderson and Nelson were working a layer of gravel 2 to 3 feet thick, overlain by 40 feet of barren soil and sand, which was removed by hydraulicking. The gravel was said to carry enough gold to justify the expense of removing the thick overburden. On the south border of the river above the Kilgore property, the Rev. Mr. Ratschkowsky had used a suction pump mounted on a float to dredge gravel from the river bed, but with indifferent success.

The R. E. L. Frymier property, at Bonanza Bar, consists of river gravel extending along the north bank for 4¾ miles and back from the channel for nearly half a mile. For the past year or more J. C. Barr had been testing the gravel and trying different methods of recovery. The plant, as set up in November, 1934, consisted of a tractor-drawn dump scraper delivering the gravel to a belt conveyor that carried it to a trommel screen, where it was washed. The material under one-eighth inch in size was discharged into a sluice box 64 feet long, set on a grade of ⅜ inch to the foot and lined with burlap. Mr. Barr stated that about 40 per cent. of the material passed through the screen

and that about 1 per cent. of this fine material was black sand, which carried the gold. He proposed to substitute ground-sluicing or a gravel pump for the scraper and belt conveyor, and to pass the black sand over concentrating tables to amalgam plates. Various assays of the black sand were reported to show an average value of about $1 in gold (at $35 an ounce) per cubic yard of gravel. Samples taken by the writers from different layers of gravel at several places on the property indicated approximately this average value when panned.

In the vicinity of Rupert, where the Snake River flows in a shallow channel across a wide plain, there are extensive gravel deposits along each bank. Samples of gravel were taken from several road-gravel pits, and when panned, all showed colors that were equivalent to perhaps 20 to 50 cents a cubic yard. Beside the river near the highway bridge 4½ miles east of Rupert, several men were working with equipment consisting of a centrifugal pump, which lifted water from the river to a flume that discharged against a gravel bank. The material thus loosened was shoveled and washed into a sluice lined with burlap, to catch the black sand and gold.

Several years ago a plant was installed near King Hill, to work the gravel by a steam shovel and separate the gold by flotation. This enterprise did not prove successful, and the plant was dismantled. Since then several men have made fair wages by washing selected deposits of the gravel in this area. The river is here entrenched in a lava channel, but on the north side there is a wide bench covered with boulders and coarse gravel, with a relatively small amount of sand. The richest deposits seem to consist of layers of gravel from a few inches to 1 or 2 feet thick, beneath the surface soil but overlying coarse sand. C. E. Pugh, who has worked gold-bearing gravel in the King Hill district since 1922, stated that most of these thin deposits of gravel contain about 40 to 80 cents in gold to the cubic yard, and that selected places have yielded more than $1 to the yard.

The gold-bearing gravel of the Snake River, like some low-grade placer deposits of the north Pacific coast described by

Pardee,[4] can probably be worked profitably by small operators in many places where the gold has been locally concentrated. Large-scale operations have not thus far been successful.

Along the Columbia River in Washington there are deposits of gold-bearing gravel similar to those of the Snake River. Along the Columbia above the Grand Coulee Dam there were five placer-gold workings in the fall of 1934, ranging in capacity from 100 to 1,200 cubic yards of gravel a day. These operations should yield data of value on the feasibility of working the gravel on a moderately large scale.

It is significant that the rate of gold production in the United States did not greatly increase during 1933 and 1934, notwithstanding the increase in the price of gold. It is possible that an increasing proportion of the gold produced in this country during the next few years will be obtained by small operators from low-grade deposits, including the gravel of the Snake River.

THOMAS H. HITE,
GERALD A. WARING.

MOSCOW, IDAHO
AND
U. S. GEOLOGICAL SURVEY
WASHINGTON, D. C.

SECONDARY CHARACTER OF PEBBLE AND RUBY JACK OF THE JOPLIN DISTRICT.

Sir: In a paper by W. H. Newhouse on the temperature of formation of the Mississippi Valley lead-zinc deposits,[1] giving the temperature of formation of sphalerite from various localities, as determined from liquid inclusions, there are listed (p. 748) nine occurrences of sphalerite from the Mississippi Valley, five of which are from the Joplin District. The specimens from three of these five localities are described as " dark brown crystals from cavities, also 'pebble jack'," from Joplin; " pebble jack," from

[4] Pardee, J. T.: Beach Placers of the Oregon Coast. U. S. Geol. Survey Circ. 8, 1934.

[1] Newhouse, W. H.: The Temperature of Formation of the Mississippi Valley Lead-Zinc Deposits. ECON. GEOL., vol. 28, pp. 744–750, 1933.

Tuckahoe; and "ruby blende, well formed crystals resting on chert," from Joplin; and their temperatures of formation are given as 125°–135° C.; 115°–125° C., and 90°–105° C., respectively.

I have seen much pebble and nugget jack in the mines in the vicinity of Joplin, more especially in those east of the city, and have examined carefully the mode of occurrence of this type of ore. It was noted in all instances in mines in which the ore body was considerably weathered. The pebble jack occurred well below ground-water level, and was always found disseminated either in soft, clay-like selvage derived from jasperoid, or in the dark-colored muds that represented a still more advanced stage in the weathering of jasperoid. Pebble jack, as I understand the term, consists of free crystals in a soft, clay-like matrix or mud, so that when washed, a handful of the crystals suggests an aggregate of pebbles. After washing, much of the pebble jack still retains, in some of its surface hollows, traces of the soft, gray selvage in which it was developed. A sample of this, examined under the microscope, is seen to consist essentially of microscopic crystals and grains of quartz.

It may be noted in passing that selvage has a marked tendency to concentrate calcium sulphate from underground waters; and if a drop of distilled water is placed for a moment on a remnant of selvage on pebble jack, and then transferred to a glass slide, it will usually yield, on evaporation, numerous microscopic crystals of gypsum.

Jasperoid is the chief gangue of the ores of this region, and it is my belief that the disseminated ore in this rock was deposited because of the reaction of underground solutions with active hydrocarbons in the deformed limestone which the jasperoid replaced. It would seem that the selvage and mud derived from the jasperoid through weathering still contain sufficient active hydrocarbons to render them favorable to the deposition of secondary sulphides. Whatever the cause, secondary sphalerite is apparently deposited more commonly and more abundantly in these than in other parts of the ore runs. It is this secondary

sphalerite that forms the pebble and nugget jack, and much of the ruby jack as well.

The zinc and lead sulphides formed in soft selvage differ from the deposits of open cavities in that their crystals are on the whole considerably smaller, and since they are disseminations, they exhibit no surface of attachment. On the other hand, the pebble jack differs from the ore disseminated in jasperoid in that the crystals are on the average larger than those in the jasperoid, have a smoother surface and a noticeably different color, this ore ranging from ruby to black jack, whereas the sphalerite of the jasperoid is a rosin jack. Moreover, the original sphalerite always disappears from jasperoid before the latter has weathered appreciably, so that pebble jack cannot represent the original disseminated ore. Also, some of the pebble jack examined contained considerable included selvage in microscopic grains and occasional aggregates, and must therefore have been formed after the development of the selvage. The pebble jack is thus unquestionably a secondary ore, deposited quite recently from waters containing the oxidized products of primary sphalerite.

The ruby blende or ruby jack is similar to the pebble jack in that it, too, is a secondary ore. In the runs about Joplin, in addition to its occurrence, like pebble jack, in mud and soft, clay-like selvage, it was found in abundant small crystals in very porous, soft, weathered jasperoid, having been deposited in cavities resulting from the weathering of this rock and the leaching out of its original ore. The deep reddish-amber color of the ruby jack, its greater transparency, its smooth crystal faces, its growth on exposed surfaces and in cavities, its definite surface of attachment, and its occurrence in greatly weathered, porous jasperoid, all serve to distinguish this type of sphalerite from the disseminated rosin jack of the unaltered jasperoid, and show beyond question that it is a secondary ore.

Ruby jack also occurred, to a limited extent, in openings in the brecciated cherts, usually in larger and more deeply colored crystals than those just described, but here, again, on or near weathering jasperoid. I have also seen small crystals of ruby jack in

a somewhat porous, granular mass of smithsonite, this sphalerite having been formed during or since the development of the smithsonite. In the sheet ground of the Webb City-Carterville area, ruby jack occurred on jasperoid and chert surfaces in cavities. In this area it was interpreted by Bain, Siebenthal and myself as secondary ore. It closely resembled the ruby jack of the runs, and, like the latter, was quite different from the very much larger, much less transparent, usually brownish crystals of primary sphalerite ordinarily found in the cavities of the ore bodies. It was not common but was noted here and there in small, often minute, clear crystals of a deep amber color. Nor did it occur, as a rule, with the larger crystals of the cavities, but was found either isolated, in scattered crystals or small aggregates, or else associated with moderately small bright crystals of galena, which were also believed to be secondary.

If, then, both the pebble and ruby jack are recently formed secondary ores, the conclusion drawn by Dr. Newhouse from his study of their fluid inclusions—that the solutions from which the ores were deposited were thermal—would seem to be unwarranted, since it is certain that these secondary ores of the Joplin district have been formed at normal underground temperatures. Moreover, although these secondary ores, like the primary ores of the cavities, contain strongly saline fluid inclusions, it seems beyond question that the former were deposited from ordinary, non-saline circulating waters.

These are not the only difficulties which I see in the way of accepting Dr. Newhouse's recent conclusion, but the others are discussed in another paper.

W. S. Tangier Smith.

Palo Alto, California,

REVIEWS

Die Lagerstätten der Edelsteine und Schmucksteine. By O. STUTZER AND W. FR. EPPLER. Pp. xvii + 567, figs. 154. Gebrüder Borntraeger, Berlin, 1935. Price (paper), 43.50 M.

This is volume No. 41 of the "Wichtigsten Lagerstätten der 'Nicht-Erze,'" edited by Dr. Stutzer. To those familiar with the earlier volumes of this series the thoroughness with which the gems and precious stones have been treated in the present volume will not be surprising. Dr. Stutzer is responsible for the article on diamond, which constitutes the first part of the book, and comprises 216 pages. In its preparation he was assisted by E. Kaiser on So. African diamonds, by von Freyberg on those of Minas Geraes, by Polinard on those of the Congo, and by Hoffman on artificial diamonds. The discussion is very comprehensive. It covers all phases of the subject, including occurrences, utilization and industry, and is well illustrated by pictures and maps; but it contains very little that cannot be found in the published literature of the subject. However, since the literature is widely scattered and much of it is difficult to obtain, the chapter furnishes a convenient summary of it.

The part of the volume that deals with gems, etc., other than diamonds, does not pretend to be complete because, (1) the geological environment of many of the best known occurrences has been inadequately described, and (2) because many of the less important sources of the material are in the hands of natives who are unwilling to have their locations made known. However, all the information available to the author has been incorporated in the text. It gives, therefore, like the part on diamonds, an excellent summary of our knowledge of the many gem and ornamental stones of which it treats.

The book is furnished with a very full place-index as well as one of subjects (Sachregister). The only unfavorable comment that may be made upon it is that its trade statistics are not brought up more nearly to date.

W. S. BAYLEY.

Introduction aux Études Minières Coloniales. Société d'Éditions Géographiques, Maritimes et Coloniales, Paris, 1934.

The "Bureau d'Études Géologique et Minières Coloniales," organized to make known the mineral resources of the French Colonial possessions

and to facilitate their exploration and development, has published several previous volumes. The first, "La Géologie et les Mines de la France d'Outre-Mer," was followed by detailed descriptions of the resources of coal, iron, and several non-ferrous metals; other similar descriptions will follow.

The volume under review is the outgrowth of a series of conferences held during the winters of 1932–1933 and 1933–1934, at which were discussed the special problems that confront the geologist and the miner working in the colonies.

The result is a book packed with useful information. The chapters that deal with organization, transport, and hygiene refer specifically to conditions in the French colonies, but their advice is applicable to all primitive tropical regions. The discussions of tropical weathering and of alluviums are important contributions, based as they are on extended study in regions where deep lateritic soils, which themselves may be economically important, blanket most outcrops; they turn the prospector to the careful study of stream alluviums for indications of rock types and of valuable minerals.

The scope of the work is indicated by the chapter headings: I, The main types of mineral deposits; II, Superficial alteration of aluminous silicate rocks in tropical countries and the formation of mineral deposits; III, Practical study of alluvial deposits; IV, Geophysical methods; V, Organization of expeditions; VI, Hygiene in Colonial installations; VII, Transport in prospecting and developing Colonial mineral deposits; VIII, Relations with natives; IX, Microscopic study of coal; X, Microscopic study of metallic minerals; XI, Commercial considerations relative to non-ferrous minerals and metals; XII, Trade relations in metals between the Mother Country and the Colonies. Each chapter is followed by a bibliography.

These diverse topics will be commented upon separately. Naturally, the emphasis will be on those of specific geologic interest.

Chapter I, on types of mineral deposits, by L. de Launay, is a brief, lucid exposition of economic geology which necessarily suffers somewhat from over-simplification, but reflects the author's fund of knowledge.

The practical value of the study of ores is considered first. The average composition of the crust is given as a background against which the extraordinary concentration of metals in an economic deposit stands out, and a pre-crustal heterogeneity is invoked to explain the marked localization of certain metals.

The discussion of mineral genesis that follows indicates the need for a knowledge of the general geology of a region if mineral investigation is to be planned wisely. The geologist may not be able to locate the specific places where mineral deposits will be found but he can delimit the regions

where they may occur and, of equal importance, he can eliminate unlikely areas.

Chapter II, on laterites and lateritization, was written by A. Lacroix, whose studies of these phenomena cover many years. It emphasizes the fact that one of the remarkable features of the geology of humid tropical lands is the lateritic alteration of aluminous silicate rocks accompanied by complete oxidation and the formation of a deep red soil. The red blanket or "manteau sanglant" that covers Madagascar is cited as an example. Although such alterations have important agricultural consequences, it is noted that they have not been studied in sufficient detail in the French Colonies. This lack is being rectified at present as one outcome of the program of study of which this book is a part.

Part I of this chapter, on types of lateritic alterations, commences with a brief historical review of the subject. In 1807, in India, Buchanan proposed the term laterite from "later" brick, because of the use of these materials in their manufacture. Up to 1898 the term was used without chemical or mineralogical implications, but at that time Max Bauer showed that laterites are composed of iron, aluminum, and titanium hydrates, whose proportions alone vary with the character of the original rock. He concluded that they are the normal result of the weathering of rocks in the tropics, as opposed to the formation of aluminous silicates, or clays, in temperate regions.

This conclusion was generally adopted without verification, although from 1901 on, the presence of subordinate quantities of clayey material was recognized in the true laterites. In 1911 L. L. Fermor published his work on the laterites of India, and in 1913 Lacroix himself made a detailed examination of the laterites of New Guinea and Soudan. Those studies, prosecuted on carefully selected samples that represented every stage of the transformation from fresh rock to complete lateritization, led to the following classification:

I. Laterites	90–100% lateritic material.
II. Argillaceous laterites	50– 90% lateritic material.
III. Kaolin and argillaceous laterites	10– 50% lateritic material.
IV. Kaolin and lateritic argillites	less than 10% lateritic material.

These names are qualified, depending on whether the constituents are dominantly crystalline or amorphous. That is, laterites are respectively either gibbsitic or bauxitic laterites. Laterite itself is regarded as the end-product of the process of lateritization. It lies at the surface and forms a layer which is thin relative to the depth of partial lateritization.

Two zones are distinguished: (1) "Zone de départ," in contact with unaltered rock and representing the initial alteration. This is arbitrarily limited to that part in which the primary rock structure is still evident, and

it is characterized by increasing discoloration from the bottom up. The silicates are progressively altered, and the alkalies, lime, and magnesia are nearly completely leached throughout the zone.

The gibbsitic argillaceous laterites of New Guinea, Soudan, and Madagascar belong to this category and are marked by an abrupt transition from fresh rock to that in which all the primary minerals are altered. On the other hand, the kaolins and lateritic argillites evidence a gradual alteration of mica and kaolinization of feldspar. Chemical analysis alone reveals the presence of aluminum hydroxide in these. In New Guinea these two types result from the alteration of different kinds of rocks but in Madagascar they are independent of the primary rock. (2) "Zone de Concrétion," above zone (1), is characterized by a concretionary structure and an increasingly intense red color as the surface is approached. The alteration is complete in the upper part where, in highly ferruginous rocks, a crust may form which is sufficiently rich in iron to constitute an ore.

The types of laterite that form in zone (2) are directly related to those of zone (1). Gibbsitic laterites form above the corresponding argillaceous laterites; and colloidal bauxitic laterites, above the kaolins and lateritic argillites. Rocks high in iron give a pisolitic ferruginous crust.

Lacroix refers the reader to his former works (listed in a bibliography) in connection with the detailed mineralogy of laterites and the mechanism of the transformation. With reference to the latter point he states here that, since lateritization and kaolinization are known to occur together, and their products are mingled in all proportions, the two alterations must be regarded as differing in degree rather than in kind. The fundamental point that requires further elucidation is the manner of formation of the hydrated alumina of the laterites. The essential requisites for this transformation are high temperature and humidity. The action is most intense when rainy seasons alternate with relatively dry ones. Under these conditions the water table alternately rises, and salts are removed, then falls, and ferrous bicarbonate solutions rise to the surface by capillarity, where under the influence of oxygen, aided possibly by biochemical reactions, ferric hydrate is precipitated. The concentration of aluminum hydroxide must occur under the same conditions, but the exact mechanism of the transformation and the influence that causes it to form in preference to kaolin are not clear.

The control that the ground-water level exerts over the formation of laterites, as noted above, is emphasized by the fact that, as the rivers of a region carve their valleys deeper and the water table is permanently lowered, laterite ceases to form. It becomes "dead laterite" even though the process continues at lower levels. The cessation of the process of lateritization may result as well, of course, from radical climatic change.

Part II of this chapter describes the effect of such alterations on the economic extraction of valuable minerals. The liberation of graphite flakes from the schists of Madagascar, and tin from the pegmatites of Malaysia by lateritization of the inclosing rock greatly facilitates mining. Lateritization of the gangue is also important in the alluvial and eluvial concentrations of corundum and garnet in Madagascar, since it permits the transporting agents to destroy the valueless material readily and thus to concentrate the important mineral.

Destruction of the gangue of metallic minerals is accompanied by reorganization of the metals into new compounds. Iron is concentrated as pisolitic or nodular hydroxides accompanied by some alumina and titanium. True bauxite is formed only when the original rock was high in alumina and low in iron, and then only in the upper or concretionary zone.

The mode of concentration of cobalt, zinc, manganese, and gold under the same conditions is also briefly described.

Chapter III, by L. Thiebaut, is a practical study of alluvial deposits written as a guide to prospectors. It describes the alluvial deposits and emphasizes the necessity of their systematic study because of the dense vegetation, thick humus, and lateritic cover that blanket the bed rock. It is often the only way to locate mineral deposits in such areas. The alteration, and the destruction or preservation of the different minerals released from the rocks and transported by streams, are explained. The probable distribution of light and heavy minerals in gravel beds, the methods of taking samples and their concentration are detailed. The more careful study of the concentrates is then outlined with particular emphasis upon specific gravity, hardness, index of refraction, and optical study.

Chapter IV, by C. Schlumberger, deals with geophysical prospecting. These methods find their greatest use to date, in regions where the obvious deposits have been located and exploited, since the cost and the difficulty of transporting delicate instruments in undeveloped lands is great. However, where the cost is not prohibitive, geophysics may be applied profitably.

Two tables are included here. The first outlines the various geophysical methods, the ordinary conditions under which each would be used, and the practical difficulties involved. The second lists a number of problems together with the method to be employed in their solution. These are not exhaustive but would serve as a guide to the inexperienced attempting to determine the best way to attack a problem. The special methods are then described in greater detail.

The important feature of this discussion is the emphasis placed upon the necessity of geological knowledge to direct the geophysical investi-

gation and to interpret the results. The future of geophysics and the certainty of its greater development are both considered and a plea is made for men trained in both physics and geology.

Chapters V, VI, VII, and VIII deal with the specific difficulties confronting exploring parties in the French Colonies, and although they are full of sage advice, they need not be considered here. Some note should be made however of Chapter V, "The Organization of Expeditions," by P. Lecomte. It defines the relations between the prospector, the prospective buyer, and the expert sent to investigate the deposit. It depicts many of the pitfalls for the unwary expert and for the outsider inveigled into investing his money in an incompletely explored deposit somewhere in the Colonies. It also emphasizes the difficulties and the expense attending serious investigation, and proposes that a geologist and an engineer should always go together, the first to study the ground, the second to pass upon the economic feasibility of the venture.

Chapter IX, by André Duparque, is devoted to the microscopic study of coal because of the major importance of coal in the economic life of any region. The description is accompanied by 12 illustrations showing the types of bituminous coal of northern France studied by the author's recently developed methods of polishing and etching. These methods are explained in considerable detail.

The micro-constituents of coal are listed under two general heads: (1) Organic Débris, (2) Amorphous Substances.

The first consists of spores, cuticle, resins, and fragments of woody tissue. The second compose the amorphous cement derived from the alteration of albuminoids, carbohydrates, and celluloses, and to a lesser degree from the resins, cuticle, and wood of plants.

It is interesting to note that the débris is so fine as to be readily transportable by wind or water. The sorting of the constituents is so complete that the author describes its accumulation as a mechanical precipitation and that of the amorphous cement as a chemical one. All the materials are transported from their place of origin.

The macroscopic classification of coal is described but the conclusion is reached that microstudy is the only basis for serious work on coal. Such investigations in conjunction with stratigraphic and paleontological studies serve to indicate the characters of the beds and their horizontal variations and so aid in their development. They also indicate the nature of the constituents and help the technician to determine why certain coals yield particular substances on distillation.

Chapter X, microscopic study of metallic minerals, by J. Orcel, outlines the advantages of this method, particularly in working out the most economic milling methods and in furnishing a basis for the estimation of reserves founded on an intelligent theory of genesis. The methods

employed in such studies have been introduced into France comparatively recently, and consequently considerable space is devoted to them, particularly to the use of polarized light, reflecting power, and microchemical methods. The descriptions of many minerals follow and are accompanied by 24 good photomicrographs. In conclusion the scientific importance of such studies is emphasized, although the practical aspects are more important in this connection.

The last two chapters relate to commercial considerations and particularly to the trade relations between France and her colonies. The last chapter is illustrated by diagrams showing the movements of metals, production, and stocks on hand.

All in all, this is an excellent publication which assembles a great diversity of topics related to mineral development. It is well worth careful study by economic geologists of all nationalities, whether or not they plan to work in the tropics.

WILLIAM M. AGAR.

COLUMBIA UNIVERSITY,
NEW YORK CITY.

Geologie von Asien. Bd. I, Teil 1. By K. LEUCHS. Gebrüder Borntraeger, Berlin, 1935. Pp. viii + 236, figs. 69. Price (paper), 18.40 M.

Geologie von Asien is one of the valuable series of the Geologie der Erde published under the editorship of Dr. E. Krenkel. Other members of the series already published deal with the geology of Africa, Europe and South America. Each purports to give a resumé of the facts known about the geology of the continent of which it treats, together with a summary of the theories that have been proposed to explain its structure, etc. The account of the geology of Asia will be embraced in two volumes, each in two parts. A part of the first volume now appearing deals with the physiography of the continent as a whole and its structure and development. This occupies 35 pages. The greater portion of it, however, discusses in some detail the geography and geology of Northern Asia. The second brochure will discuss Central Asia; Volume II will treat of Eastern and Southern Asia, and a part of Western Asia. The Urals are discussed in the volume on Europe, and the Arabic Peninsula in that on Africa.

The geology of North Asia is treated under three principal heads; (1) stratigraphy and igneous rocks; (2) tectonics; and (3) mineral deposits. The first two sections appear to furnish satisfactory accounts of the general geology and the structure of the region, based on the work of 80 or more geologists. The third section gives a brief summary (15 pages) of its mineral resources.

The great value of the publication to non-Russian geologists is the

great amount of material it has gleaned from Russian sources that would otherwise be inaccessible to them.

The book is provided with a list of the more important publications that have appeared since the list given in Obrutschew's "Geologie von Siberien," in 1925, and an index of about 400 places.

W. S. BAYLEY.

The Fiord Region of East Greenland, by LOUISE A. BOYD and others. Pp. 381, figs. 361, pls. 11, maps. 10. American Geographical Society, Spec. Pub. 18, New York, 1935. Price, $4.00.

This pleasing book depicts the Louise A. Boyd Expedition to East Greenland in 1933. The story is told largely by some 350 beautiful photographs, excellently reproduced, showing fiords, mountains, glaciers, icebergs, geologic structure, physiographic features, and culture. The text consists of a narrative by Miss Boyd (57 pp.); physiographic studies by J. Harlen Bretz (88 pp.); photogrammetrical work by O. M. Miller and W. A. Wood (21 pp.); botanical lists by W. B. Drew (12 pp.); echo sounding records by C. B. Hitchcock (13 pp.); tide gauge record by O. M. Miller; and a historical outline by J. K. Wright (41 pp.).

The text, photographs and maps combined present an excellent picture of the physical features of the region and add much to our knowledge of this remote country. The author is to be congratulated upon the successful outcome of the expedition, and the American Geographical Society, on such a praiseworthy publication.

Contributions to Canadian Mineralogy, 1934. Univ. of Toronto Studies, Geol. Ser. 36. Pp. 54, pls. 5.

Contains a description of the Canadian amber at Cedar Lake, Manitoba, by T. L. Walker; descriptions of 27 metallic minerals in the silver-uraninite deposits of Great Bear Lake; and an announcement of the discovery of telluride ores at Straw Lake near Fort Frances, Ontario, and at the Eureka mine in Abitibi Co., Quebec, by Ellis Thompson. Tetradymite, gold, galena, pyrite, chalcopyrite, sphalerite, magnetite are the principal metallic minerals of the ores at both places.

In addition, Parsons gives a list of the semi-precious and ornamental stones of Canada and notes on their utilization.

BOOKS RECEIVED.

DAVID GALLAGHER.

The Contact Mining District, Nevada. F. C. SCHRADER. Pp. 41, figs. 6, maps 4. U. S. Geol. Survey Bull. 847–A. Washington, 1935.

Geology of Big Horn County and the Crow Indian Reservation, Montana. W. T. THOM, G. M. HALL, C. H. WEGEMANN, G. F. MOULTON. Pp. 200, figs. 13, pls. 15 (maps), index. U. S. Geol. Survey Bull. 856. Washington, 1935. Price, 60 cts. Not a complete survey of all parts of the region, but gives special attention to water, coal, oil, and gas resources.

The Eastern Lupa Goldfield (Tanganyika). E. O. TEALE AND F. OATES. Pp. 61, maps 3. Geol. Surv. Dept. Tanganyika Bull. 8. Dar es Salaam, 1935. Price, 5s.

James River Iron and Marble Belt, Virginia. A. S. FURCRON. Pp. 124, figs. 12, pls. 15, index. Virginia Geol. Surv. Bull. 39. University, 1935.

Information Regarding Coal and Coal Products: A List of Books and Other Sources of Information. Compiled by F. R. WADLEIGH. Pp. 63. Distributed by National Coal Assoc., Washington, D. C., 1935. Complete list of publications in English.

Kyanite and Vermiculite Deposits of Georgia. L. M. PRINDLE. Pp. 50, figs. 4, pls. 11. Georgia Geol. Survey Bull. 46. Atlanta, 1935.

Illinois Petroleum: Oil and Gas Development in 1934. A. H. BELL. Pp. 15. Illinois Geol. Survey, Press Bull. 26. Urbana, 1935.

Contributions to the Study of Coal (Illinois). C. G. BALL. Pp. 106, figs. 11. Illinois Geol. Survey, Rept. of Inves. 33. Urbana, 1935. Mineral matter of No. 6 coal bed at West Frankfort, Franklin County.

The Travertine Deposits near Port St. Johns (South Africa). W. KUPFERBURGER. Pp. 15. Dept. Mines, Union of So. Africa, Pretoria, 1935.

Gypsum in the Union of South Africa. B. WASSERSTEIN. Pp. 35. Dept. Mines, Union of So. Africa, Pretoria, 1935.

Federated Malay States, Report of the Geological Survey for 1934. Pp. 16. Batu Gajah, 1935.

Water Supplies in the Anglo-Egyptian Sudan. G. W. GRABHAM. Pp. 42. Sudan Govt., Bull. 2. Khartoum, 1934. Price, 1s, 8d.

Carte Geotechnique de la Suisse (scale 1:200,000), Blatt 2: Luzern-Zurich-St. Gallen-Chur. P. NIGGLI AND F. DE QUERVAIN. Comm. Geotech. de la Soc. Helvet. des Sci. Nat. Bern, 1935.

Uganda, Report of the Geological Survey for 1934. Pp. 12. Entebbe, 1935.

Berg- und Aufbereitungstechnik: Bd. I. Technische Grundlagen des Tagebaues, Teil 2: Forderung und Verkippung. A. Ohnesorge *et al.* Pp. 225, illus. 297, tables 41, index. Wilhelm Knapp, Halle (Saale), 1935.

Outline of the Principles of Geology (revised). R. M. FIELD. Pp. 198, figs. 117. Barnes & Noble, New York, 1935. College Outline Series for first year courses in general and introductory geology.

Ontario Dept. of Mines, Annual Report, Vol. XLIII, Pt. III, 1934. Pp. 89, maps. Geology of the Swayze Gold Area, by H. C. RICKABY; Geology of the Makwa-Churchill Area, by H. C. LAIRD. Toronto, 1935.

The Canadian Mineral Industry in 1934. Pp. 119. Canada Dept. of Mines, Mines Branch, Bull. 760. Ottawa, 1935. Reviews by staff of Mineral Resources Division.

Quebec Bureau of Mines, Annual Report for 1933; Part D. Marsoui Map-area, Gaspé Peninsula, also Report on North-Central Gaspé, by I. W. Jones; Northwest Part of Lac-Saint-Jean Region, by B. T. DENIS; Western Témiscouata Region, by H. W. MCGERRIGLE; Upper Gatineau Region, by J. A. RETTY; Geology of North Shore, Manicouagan to Godbout, by C. FAESSLER. **Part E.** Commercial Granites of Quebec, III: North of St. Lawrence River (2d section), by F. F. OSBORNE. Quebec, 1934.

Geological Map of Central Brazil: scale 1:2,750,000. 35″ × 35″. Map of Petroleum Survey of Parts of Southern Brazil, Uruguay, Argentina, and Bolivia: scale 1:2,750,000. 35″ × 35″. By V. OPPENHEIM. Min. da Agric. do Brazil, Rio de Janeiro, 1935.

Oil and Gas Possibilities of Western Whatcom County, Washington. S. L. GLOVER. Pp. 69, figs. 1, structure map. Washington Dept. Conserv. and Devel., Rpt. of Inves. No. 2. Olympia, 1935.

Investigations in Ore Dressing and Metallurgy. W. B. TIMM, ET AL. Pp. 194. Canada Dept. Mines, Mines Branch, No. 744. Ottawa, 1934. Forty short papers.

Gold in the Gold Coast. N. R. JUNNER. Pp. 76, map. Gold Coast Geol. Surv. Mem. 4, 1935. 8/. General geology; description of mines and prospects; appendix on mining law by R. P. WILD; geologic map in color, scale 1:500,000, covering Gold Coast south of 7° 30′ latitude.

Imperial Institute, Annual Report, 1934. H. A. LINDSAY, Director. Pp. 54. Administrative report.

Estudos Geofísicos no Estado do Rio Grande do Sul (Brazil). M. C. MALAMPHY. Pp. 50, figs. 39. Serv. Geol. e Min. Brazil, Bol. 68. Rio de Janeiro.

Geologia do Municipio de Lages, Santa Catarina (Brazil). G. DE PAIVA. Pp. 23, sketch map. Serv. Geol. e Min. Brazil, Bol. 69. Rio de Janeiro.

SCIENTIFIC NOTES AND NEWS

Joseph P. Connolly has been appointed president of the South Dakota State School of Mines to succeed the late C. C. O'Harra. Dr. Connolly has been professor of mineralogy, petrography, and economic geology at the School of Mines since 1919, and vice-president since 1926.

Sir John Flett, Director of the Geological Survey of Great Britain, will retire on October 1st, and Bernard Smith, now Assistant to the Director, will become Director.

F. L. Ransome, professor of economic geology at the California Institute of Technology, has been elected an honorary member of the Geological Society of Belgium.

Charles W. Wright is acting as mineral specialist for the U. S. Bureau of Mines, with headquarters at Rome, Italy. His address is in care of the American Consul at Rome.

Thomas F. Sutherland, for some years Acting Deputy Minister of Mines for Ontario, has now been appointed Deputy Minister of Mines, succeeding Thomas W. Gibson, retired.

F. J. Alcock is surveying the Lake Athabaska gold field in northern Saskatchewan for the Canada Geological Survey.

H. Foster Bain has returned to New York after an extended trip around the world.

B. S. Butler, professor of geology at the University of Arizona, has in preparation a complete geological report on the Tombstone district, an area previously unreported.

John J. O'Neill, who has been on the staff of McGill University, Montreal, since 1921, has now been appointed dean of science in the faculty of arts and science.

D. C. Sharpstone, formerly chief geologist at Roan Antelope Copper Mines, is directing the development of the Whitewater group of gold mining claims near Tulsequah, British Columbia, about forty miles east of Juneau, Alaska.

Frederick G. Clapp, after a stay of some months in Haiti and the Dominican Republic, has now returned to his New York and Bronxville offices.

Charles F. Jackson is now acting head of the Mining Division of the U. S. Bureau of Mines, taking the place of Charles W. Wright.

M. F. Fairlie, of the Mining Corporation of Canada, has resigned to take up private practice as consulting engineer in Toronto.

R. W. Brock, esteemed Associate Editor of this Journal, was instantly killed in an airplane crash north of Vancouver on July 30. Mrs. Brock died of injuries the following day.

The late Dean Brock attended Queens University and Heidelberg, was successively professor of geology at Queens, Director of the Geological Survey of Canada, Dean of the Faculty of Applied Science at the University of British Columbia. He directed a geological survey of Hong Kong, was chairman of the Vancouver Harbor Commission, and last May was named president of the Royal Society of Canada.

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